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GEOPHYSICAL METHODOLOGY STUDIES FOR MILITARY GROUNDWATER EXPLORATION

by

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This report contains the results of geophysical surveys at two sites: White Sands, New Mexico and Fort Carson, Colorado. The geophysical surveys, seismic reflection, seismic refraction, shear wave refraction and reflection, and electrical resistivity, were used in an integrated fashion to detect and assess groundwater potential at a number of locations at each site. The locations presented various geological and groundwater conditions. The

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results of the surveys varied from fair to good. Factors which contributed to a successful assessment of groundwater potential were: a) geology consisting of coarse-grained sediments, b) limited knowledge of geology, c) knowledge of all available geologic information. Factors which hindered the assessment of groundwater potential were: a) geology consisting of fine-grained sediments, b) complex geology and topography, c) no prior knowledge of the geology available. Software developed during this study was designed to allow unskilled military personnel to interpret refraction and reflection data on a small, field-portable microcomputer.

EXECUTIVE SUMMARY

This report contains the results of geophysical surveys at two sites: White Sands, New Mexico and Fort Carson, Colorado. The geophysical surveys, seismic reflection, seismic refraction, shear wave refraction and reflection, and electrical resistivity, were used in an integrated fashion to detect and assess groundwater potential at a number of locations at each site. The locations presented various geological and groundwater conditions. The results of the surveys varied from fair to good. Factors which contributed to a successful assessment of groundwater potential were: a) geology consisting of coarse-grained sediments, b) limited knowledge of geology, c) knowledge of all available geologic information. Factors which hindered the assessment of groundwater potential were: a) geology consisting of fine-grained sediments, b) complex geology and topography, c) no prior knowledge of the geology available. Software developed during this study was designed to allow unskilled military personnel to interpret refraction and reflection data on a small, field-portable microcomputer.

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PREFACE

This work was performed during the period of August 1, 1982 to July 31, 1983 by personnel of the Exploration Research Laboratory (ERL), Colorado School of Mines (CSM), Golden, Colorado. The work was performed for the U.S. Army Mobility Equipment Research and Development Command (DRDME-GS), Fort Belvoir, Virginia, as authorized and funded by PIIN DAAK 70-82-C-0102, August 1, 1982.

The work was performed by Mr. Brian D. Rodriguez, and Mr. Michael H. Powers. This report was prepared by Dr. Phillip R. Romig and Messrs. Rodriguez and Powers.

The overall project was a cooperative effort with the Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), U.S. Army Engineering Waterways Experiment Station (WES), Vicksburg, Mississippi. Principal Investigators for WES were Mr. Dwain K. Butler and Mr. Jose L. Llopis. Information was freely exchanged between CSM and WES during this investigation.

Dr. James K. Applegate was the Principal Investigator during data acquisition, processing and interpretation, and was succeeded by Dr. Phillip R. Romig during the report preparation phase. Mr. Brian D. Rodriguez was the Project Manager, and Mr. Michael H. Powers was the Research Assistant.

INTRODUCTION

Objectives

The objectives of the CSM (Colorado School of Mines) work effort were to evaluate existing field methodology, equipment, and interpretation methodology of the geophysical methods seismic refraction, seismic reflection, and DC resitivity in order to determine their integrated feasibility for near-term military groundwater detection application.

Background

Previous studies into the use of geophysical methods for detecting groundwater have shown that no magical "black box" exists that allows the definitive location of groundwater (e.g. Applegate, et al, 1982). Rather, it appears that multiple geophysical methods are useful in an integrated interpretation mode. This is because changes in geophysical parameters associated with changes in rock properties due to the presence of groundwater are not unique. This creates ambiguities in the interpretation of any single geophysical method with regard to groundwater detection. The use of multiple geophysical methods, which measure different rock properties, reduces the ambiguities and allows a better assessment of the presence of groundwater. Furthermore, the use of methods which measure parameters related to the rock properties that are most significantly altered by the presence of groundwater increases the possibility of direct detection. The most sensitive rock properties are seismic velo-

city and electrical resistivity, hence, the CSM work effort concentrated on the seismic and electrical methods.

For the near-term solution, the logical research approach is to field test existing methodology to assess what developments are needed for military groundwater detection application. These developments should take the form of hardware development, signal processing development, and/or interpretation methodology development. This development work must be predicated on an empirical basis as well as on theoretical considerations. Hence, the CSM work effort evaluated existing field techniques, equipment, and interpretation methods for seismic refraction, seismic reflection and DC (direct current) resistivity to determine the feasibility of implementing the near-term solution. Seismic refraction, seismic reflection, and DC resistivity have been used extensively for many years, and the basic theory is well-described in many text books (e.g. Griffiths and King, 1969; Parasnis, 1979; Telford et al, 1976). In a previous MERADCOM report, Applegate, et al (1982) comprehensively discussed the applications of field procedures for seismic and electrical methods in groundwater exploration.

Approach

The seismic methods that were investigated included seismic refraction (which is traditionally used but in this study was refined and modified) and seismic reflection, which is normally used for much deeper targets but proved to be useful as a cross-check and an extension of the refraction data set. In both refraction and reflection cases, shear waves were used in addition to the commonly used compressional waves. The DC resistivity sounding method was investigated by WES (Waterways Experiment Station). The methods were evaluated for their effectiveness in detecting groundwater in an integrated manner for the following three cases: (1) no prior knowledge of geology, (2) limited knowledge of the geology, and (3) all available geologic information known. Each of the methods was also evaluated for field methodology and equipment durability and availability. An integral part of the evaluation of the interpretation methodology for the seismic methods included extensive development of user-friendly software, thereby lowering the level of expertise required for the processing and interpreting of the data by military personnel while allowing a rapid and easy reduction of the data.

INVESTIGATION

Documentation of Field Sites

Two field sites were selected, each representing a common groundwater occurrence. White Sands Missile Range, New Mexico, was the site for an alluvial aquifer with an unconfined water table. Fort Carson, Colorado, was the site for a confined (artesian) aquifer.

Four locations were selected at the White Sands site (Figure 1), each near a water supply well, test well, or borehole. Thus depth to groundwater was known for all these locations and varied from 60 to 450 feet. Limited borehole log information was also available. Water quality varied from fresh to brackish (Table 1). The four locations are very typical of alluvial aquifers found worldwide.

A location near White Butte at the Fort Carson site was selected (Figure 2) near a good-quality well producing water from the Dakota Sandstone artesian aquifer. The depth to the top of the aquifer at the well was about 270 feet. The thickness of the aquifer was about 100 feet, and it was confined on top and bottom by shale layers. The Dakota Sandstone outcrops about one mile to the west of the White Butte well and has a regional dip to the east of about 330 ft/mile (Butler and Llopis, 1983). Due to the rugged topography and complex near-surface geology at the well site, geophysical surveys were also conducted about one-half

Table 1

White Sands Borehole Information

Location	Depth to Groundwater	Water Quality	Geology
HTA	64 (±6) ft	fresh	Sand/gravel to 82 ft; weathered granite: 82 ft
T-14	132 (±1) ft	brackish	Sand with silt and clay, 105-220 ft; clay with sand/silt 180-430 ft
MAR-2	214 (±1) ft	fresh	Gravel, 0-112 ft clay, 112-160; gravel, 160-165; clay, 165-200; gravel, 200-210 clay, 210-225; etc., below 630 ft mostly clay
SW-19	427-514 ft	fresh	Poorly sorted sands & gravel to >900 ft

mile to the west and about one-half mile to the south. Surveys were performed parallel to the strike of the Dakota Sandstone (north-south) and perpendicular to the strike (Figure 2).

Results of CSM/WES

Field work at the two sites was performed by CSM and the Waterways Experiment Station (WES). Resistivity data at one of the White Sands locations (MAR) was provided by the USGS. Table 2 summarizes the geophysical surveys performed at the White Sands site. Location numbers correspond to the well or borehole designation as shown in Figure 1. For the seismic refraction surveys, the line length refers to the largest shotpoint to geophone spread length, while for the resistivity surveys the line length refers to the maximum electrode spacing for the Schlumberger soundings. Table 3 summarizes the geophysical surveys performed at the Fort Carson site.

A. Seismic Refraction

Seismic refraction data were processed and interpreted with software developed for a field portable microcomputer. This included computer-aided picking of first arrival events and computer-aided method-of-differences refraction interpretation. Figures 3-7 are the computer-generated velocity models.

Table 2

White Sands Geophysical Program

Location	Survey Type	Performing Agency	Line * Length	Comments
NTA-1	refraction	CSM	330 ft	*Refraction line length refers to the longest shot to geophone offset. Resistivity line length refers to the maximum Schlumberger array spacing
	resistivity	WES	600 ft	
T-14	refraction	CSM	600 ft	Perpendicular to WES refraction and resistivity
		WES	540 ft	
	resistivity	WES	1000 ft	
MAR-2	refraction	CSM	825 ft	
	resistivity	USGS	4000 ft	USGS location not the same as CSM line
SW-19	refraction	CSM WES	1650 ft 1800 ft	
	resistivity	WES	1800 ft	Perpendicular to WES & CSM refraction, centered 500 ft west of well 19

Table 3

Fort Carson Geophysical Program

Survey Type	Performing Agency	Survey Number	Line * Length	Comments
refraction	CSM	1	1650 ft	Large variation in topography along line
refraction	CSM	2	825 ft	Same location as WES-4
refraction	CSM	3	1100 ft	Perpendicular to WES-3
resistivity	WES	1	1000 ft	WES-1 & WES-2 perpendicular, crossing at mid-points
resistivity	WES	2	900 ft	
resistivity	WES	3	1000 ft	
resistivity	WES	4	1000 ft	
resistivity	WES	5	700 ft	Length limited by topography

*Refraction line length refers to the largest shot-point to geophone offset. Resistivity line length refers to the maximum current electrode spacing for the Schlumberger sounding array.

B. Seismic reflection

During the field acquisition, no special procedures were followed to collect seismic reflection information; however, an attempt was made to process the refraction data as common-depth-point (CDP) reflection profiles. Microcomputer reflection software was developed as a prototype to test the concept of a field portable reflection processing package. After the creation and utilization of basic filters, normal moveout velocity analysis, time-variable gain control and CDP stacking, it was determined that the concept is certainly viable, but the necessary programming for immediately interpretable results (enhanced signal-to-noise ratio and better plot quality) was not available within our time frame. The progressive market of microcomputer hardware has recently introduced field portable "super-microcomputers" that run pre-existing, industry standard software. This may preclude the approach of software development to fit the hardware, and may suggest the possibility of obtaining hardware to fit the software. Our data was fully processed on a mainframe computer with standard industry software. Figures 8-10 are the mainframe printouts of the reflection profiles at the White Sands site.

C. Shear waves

Shear wave data were collected only at the HTA and T-14 lines at White Sands, New Mexico. The shear-wave refraction data from both lines were processed and interpreted with software

on a field-portable microcomputer. This included computer-assisted removal of the compressional waves which allowed the shear wave first arrivals to be picked with greater reliability. Figures 11-12 are the computer-generated velocity models. Figure 13 is the shear wave reflection profile over the T-14 line.

D. Resistivity

DC resistivity sounding data were interpreted by WES (Butler and Llopis, 1983) on a mainframe computer. Also, selected resistivity data were interpreted by WES on a microcomputer.

Interpretation

A. Water saturation properties

Although the term "water table" has no precise scientific definition, it is usually used to indicate the depth at which rock pore spaces are fully saturated (Keller and Frischknecht, 1966). Of course, there is a transition zone from partial saturation above the water table to complete saturation in the water table. For the purposes of this report, the term "water table" will be used to indicate the zone of complete saturation. It is important to understand how resistivity and seismic rock properties are affected by changes in water saturation. For permeable rocks and water saturation greater than 25%, bulk resistivity varies as

$$\rho \propto \frac{1}{S^2} \qquad (1)$$

where ρ is bulk resistivity and S is percent water saturation. For permeable rocks and water saturation less than 25%, bulk resistivity varies as

$$\rho \propto \frac{1}{S^n} \qquad (2)$$

where n is between 4 and 5 (Keller and Frischknecht, 1966). From equations (1) and (2) we see that bulk resistivity varies maximally with percent water saturation in the first few tens of percent and varies minimally with percent water saturation in the last few tens of percent (Figure 14). Thus, resistivity will not only be sensitive to the water table (complete saturation), but also be sensitive to zones above the water table that are only partially saturated. Compressional velocities vary as

$$V_p = \left(\frac{k + \frac{4}{3}u}{d}\right)^{1/2} \tag{3}$$

where V_p is compressional (P-wave) velocity, k is bulk modulus, u is shear modulus and d is density. Shear velocities vary as

$$V_s = \left(\frac{u}{d}\right)^{1/2} \tag{4}$$

where V_s is shear velocity, u is shear modulus and d is density. The ratio of compressional to shear velocity is

$$V_p/V_s = \left(\frac{k}{u} + \frac{4}{3}\right)^{1/2}. \tag{5}$$

When the rock pores are completely filled with water, k greatly increases while u only slightly increases. Thus, when seismic energy encounters the water table, the V_p/V_s

ratio increases. Therefore, equations (1), (2), and (5) reveal the water saturation rock properties. As water saturation increases, the bulk resistivity decreases, greatly for the first few tens of percent and leastly for the last few tens of percent, while the V_p/V_s ratio increases.

B. No prior knowledge of the geology

The detection of the presence of groundwater for military applications will at times require only the use of surface geophysical tests with no prior knowledge of the geology. It is with this case in mind that the following assessments are made. The terms "poor", "fair", or "good" will be used to qualitatively rate the confidence level in the assessment of the groundwater potential for each site.

1. White Sands, New Mexico data

HTA-1. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good. Seismic refraction, reflection, electrical resistivity and shear wave interpretations are shown in Figure 15. If groundwater were present, it would be shallower than 95 ft., since the material below this depth has a high resistivity (1500 ohm-ft). It also would be deeper than about 10 ft., since both the resistivity (1200 ohm-ft) and the velocity (refraction: 900 ft/s, shear: 600 ft/s) are indicative of dry loose rock. There are indicatons of the presence of ground-

water below a depth of 10 ft: the refracted compressional wave velocity is equal to the characteristic 5000 ft/s velocity of shallow saturated sediments, also, the ratio of the compressional to shear wave velocity (V_p/V_s) increases at this interface from 1.5 to 1.8 (900/600 to 5000/2700). An increase in the V_p/V_s ratio will occur when a saturated layer is encountered during a seismic survey. The resistivity survey reveals a decrease in resistivity at 10 ft depth which may be an indication of groundwater, however the field sampling of the resistivity measurements was too poor to accurately model these depths. The reflection data reveals a reflector at 80 ft depth which may correspond to the high resistivity layer at 95 ft depth (1500 ohm-ft). No reflectors were detected for depths shallower than 80 ft due to the poor CDP coverage. There is another refracted interface at about 30 ft depth that is probably a change in rock type with or without the presence of groundwater. Thus, if groundwater exists, it would be either at 10 ft or 30 ft depth. Although the resistivity, refraction and shear wave surveys give only an indication of the presence of groundwater, the range of depths (10 to 30 ft) is so tight that a fair to good confidence level exists that groundwater can be found near 20 ft depth. Therefore, without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good.

MAR-2. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good. Seismic refraction, reflection, and electrical resistivity interpretations are shown in Figure 16. The resistivity survey was performed about 1/2 mile east of the refraction line and so a direct comparison of the corresponding models would assume no changes in geology. If groundwater were present, it would be at a depth near 245 ft where the resistivity corresponds very well to shallow saturated saline sediments (1 to 30 ohm-ft). It could also be at a depth above 245 ft, where there is a resistivity decrease (160 ohm-ft), but it would have to be below 155 ft where the refraction survey indicates that there is a high velocity (11,000 ft/s) layer. This velocity is too high to correspond to a shallow water table, and is most likely a high velocity layer above the groundwater. The reflection survey reveals two reflectors, one at 150 ft depth which corresponds well with the high velocity refracted layer (11,000 ft/s), and another at 235 ft depth which corresponds well with the low resistivity layer (1 ohm-ft) at 245 ft depth. Again, due to poor CDP coverage, shallower reflectors were not detected. There is also a low resistivity layer at 5 ft depth (65 ohm-ft), however the refracted layer velocity at that depth (2100 ft/s) is too low to correspond to groundwater. Thus, while the refraction survey does not give

any indicators of groundwater potential, the resistivity survey gives an indication that saline groundwater is present at a depth of about 245 ft while the reflection survey indicates that an acoustical reflector exists at about the same depth. Thus, the three models support each other fairly well yielding a fairly high confidence level that saline groundwater exists near a depth of 245 ft. Therefore, without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good.

SW-19. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is good. Seismic refraction, reflection, and electrical resistivity interpretations are shown in Figure 17. If groundwater were present it would be at a depth of around 400 ft where the refraction velocity contrast is nearly two (2.5). Generally, the characteristic 5,000 ft/S velocity will take precedence over a velocity contrast of two for shallow saturated sediments; however, for deeper saturated sediments a velocity contrast of about two is typical. Again, the resistivity sampling rate was too poor to adequately model the site, but the lower resistivity layer at a depth of 400 ft could be an indicator of very fresh groundwater. The reflection survey reveals a reflector at this depth as well. Poor CDP coverage prevented the detection of shallower

reflectors. Thus, all three models support each other very well yielding a high confidence level that groundwater exists at about 400 ft depth. Therefore, without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is good.

T-14. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is good. Seismic refraction, reflection, electrical resistivity and shear wave interpretations are shown in Figure 18. If groundwater were present, it would be deeper than 120 ft depth since the refraction survey reveals a velocity (2500 ft/s) much too slow to indicate shallow saturated sediments. The refraction survey also indicates that groundwater may exist at or below 130 ft, since the velocity (6600 ft/s) is indicative of shallow saturated sediments. The resistivity survey indicates that the groundwater is saline (12 ohm-ft) below a depth of 150 ft. Both the refracted and reflected shear wave energy apparently did not penetrate very deep, thus not revealing any interfaces at these depths. If groundwater were present, it would be below 120 ft depth and saline at 150 ft depth. The surveys are in good agreement with each other and appear to be sensitive to an aquifer. Therefore, without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is good.

2. Fort Carson, Colorado data

CSM-1. Only a refraction survey was performed at this location. Examination of the TX plot (Figure 19) reveals that laterally changing velocities exist in the subsurface (increasing slope progression is interrupted by non-systematic decreases in slope; see Figure 34 for normal slope progression indicating increasing velocity vertically) and so a straightforward geophysical interpretation at this site is impossible.

CSM-3. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair. Only a refraction survey was performed at this location. The geophysical interpretation is shown in Figure 20. If groundwater were present, it would be deeper than 30 ft depth since the velocity (1300 ft/s) is much too slow to indicate groundwater. The interface at 30 ft depth has too large a velocity (9700) ft/s) for shallow saturated sediments, however, if the aquifer were not alluvial, but artesian then it is possible that the interface at 30 ft depth is an aquifer. Because only one geophysical technique was employed, and there was no prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is only fair. This is a good example of the need for integrated geophysical surveys.

CSM-2. Without any prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair. Seismic refraction and electrical resistivity (WES-4) were performed at this site. The geophysical interpretations appear in Figure 21. If groundwater were present, it would be deeper than 30 ft depth since the velocity (1900 ft/s) is much too slow to indicate groundwater. The velocity (5500 ft/s) below 30 ft depth is typical of shallow saturated sediments. The resistivity interface at 60 ft depth (55 ohm-ft) is typical of a fresh-water aquifer. The velocity (10,000 ft/s) at about 90 ft depth is on the high side for an artesian aquifer. Thus, if groundwater exists it is definitely below 30 ft depth and probably at 60 or 90 ft depth. Therefore, with no prior knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair.

C. Limited knowledge of the geology

The detection of the presence of groundwater for military applications will most of the time have available a limited supply of geologic information. It is with this case in mind that the following assessments are made.

1. White Sands, New Mexico data

HTA-1. With limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good. Knowing that bedrock occurred around 80 ft depth, the aquifer depth has to be shallower than 80 ft. The geophysical models in Figure 15 support this knowledge. It still appears that an alluvial aquifer exists at either 10 and 30 ft depth where the velocities are typical of shallow saturated sediments. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good.

MAR-2. With limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good. Knowing that the approximate aquifer depth was around 200 ft and that the aquifer was alluvial, the geophysical models in Figure 16 appear to correlate to such an occurrence. The low resistivity (1 ohm-ft) layer at 245 ft depth correlates very well to saline groundwater below the approximate aquifer depth. The refraction velocity (11,000 ft/s) interface, does not correspond to shallow saturated sediments, but is an indicator of high velocity material above the water table. The reflector at 235 ft depth also supports this knowledge. Thus, the models support known data. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good.

SW-19. With limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is very good. Knowing that the approximate aquifer depth is around 450 ft depth and that the aquifer was alluvial, the geophysical models in Figure 17 correlate very well to this knowledge. The lower resistivity (175 ohm-ft) layer occurs at 400 ft depth and the higher velocity (8900 ft/s) interface occurs at 410 ft depth. A strong reflector also appears at 400 ft depth. There is thus a high agreement of all the models with the known data. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is very good.

T-14. With limited knowledge of the geology, the geophysical asssessment of groundwater potential at this site is very good. Knowing that the approximate aquifer depth was around 130 ft depth and that the aquifer was alluvial, the geophysical models in Figure 18 correlate very well to this knowledge. The velocity interface (6600 ft/s) at 120 ft depth correlates well to shallow saturated sediments at about that depth. The low resistivity (12 ohm-ft) layer at 150 ft depth correlates well to saline groundwater at that depth, with the possibility that fresh groundwater exists above it. Although the shear wave energy apparently did not penetrate to these depths, the refraction and resistivity surveys appear to

detect the water table. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is very good.

2. Fort Carson, Colorado data

CSM-1. Again, examination of the TX plot (Figure 19) reveals that laterally changing velocities exist in the subsurface, making a straightforward geophysical interpretation of this site impossible.

CSM-3. With limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good. Knowing that the approximate aquifer depth was very shallow, around 10 ft depth, and that the aquifer was artesian, the geophysical model in Figure 20 correlates well to this known data. The high velocity (9700 ft/s) interface at 30 ft depth is characteristic of an artesian aquifer. Thus, the refraction survey supports the known data. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is good.

CSM-2. With limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good. Knowing that the approximate aquifer depth was around 60 ft depth and that the aquifer was artesian, the geophysical models in Figure 21 appear to

correlate fairly well to this known data. The low resistivity (55 ohm-ft) layer at 65 ft depth correlates very well, but the refraction interface (10,000 ft/s) at 85 ft depth is a little deep. Therefore, with limited knowledge of the geology, the geophysical assessment of groundwater potential at this site is fair to good.

D. All available geologic information known

The detection of the presence of groundwater for military applications will at times have available all known geologic information. It is with this case in mind that the following assessments are made.

1. White Sands, New Mexico data

HTA-1. The geophysical assessment of groundwater potential at this site is good. Knowing all available geologic information, the geophysical models (Figure 22) at this site correlate well to the known data assuming a draw down of 50 ft at supply well, HTA-1. The electrical measurements reveal three resistive layers. The upper layer (1200 ohm-ft) corresponds to the dry surficial layer of loose sands and gravels. The thick middle layer (300 ohm-ft) corresponds to a bulk resistivity of moist sands and gravels, the water table, and compacted sands and gravels at depth. The lower layer (1500 ohm-ft) corresponds to basement granite. The field sampling of resistivity measurements was too poor to adequately model

the water table. The refraction survey reveals three acoustical layers. The upper layer (900 ft/s) corresponds to the dry surficial layer of loose sands and gravels. The middle layer (5000 ft/s) corresponds to the alluvial aquifer assuming a draw down of 50 ft at supply well, HTA-1. This is not an unreasonable assumption, as a 50 ft drawdown on an 82 ft deep hole corresponds to 70% of the maximum drawdown (assuming the static level is 10 ft). Johnson (1966) reports that 70% of maximum drawdown is the common design practice for optimum well operating characteristics. The lower layer (7300 ft/s) probably corresponds to a change in rock type, saturated or unsaturated. The shear wave survey reveals the same dry surficial layer of loose sands and gravels (600 ft/s) and the water table (2700 ft/s) at 10 ft depth. The reflection survey reveals a reflector at 80 ft depth corresponding to the bedrock at that depth. Thus, the geophysical models correlate with all available geologic information assuming a 50 ft draw down cone in the borehole. Therefore, knowing all available geologic information, the geophysical assessment of groundwater potential at this site is good.

MAR-2. With all available geologic information known, the geophysical assessment of groundwater potential at this site is good. Knowing all available geologic information, the geophysical models (Figure 23) at this site correlate well to the known data. The electrical measurements reveal five resistive layers. The upper three layers correspond to loosely compacted gravels. The fourth layer (160 ohm-ft) corresponds to moist compacted gravels and clays, and the water table. The lowest layer (1 ohm-ft) corresponds to saline groundwater. (Please note that the resistivity measurements were gathered 1/2 mile east of the borehole log and the refraction and reflection lines; thus, absolute depths to interfaces may not correspond exactly.) The refraction survey reveals three acoustical layers. The upper layer (2100 ft/s) corresponds to loosely compacted gravels. The middle layer (4100 ft/s) corresponds to moist compacted gravels. The lower layer (11,000 ft/s) corresponds to a high velocity clay layer just above the water table. The velocity of the saturated gravel layer is likely to be smaller than the clay layer velocity, and thus it would never be measured using the refraction method. The reflection survey reveals two reflectors, one at 150 ft depth corresponding to the same interface as the 11,000 ft/s refractor, and the other at about 235 ft depth probably corresponding to a clay layer. Thus, all the models agree well with the known data. Therefore,

knowing all available geologic information, the geophysical assessment of groundwater potential at this site is good.

SW-19. With knowledge of all available geologic information, the geophysical assessment of groundwater potential at this site is very good. Knowing all available geologic information, the geophysical models (Figure 24) at this site correlate very well to the known data assuming a draw down of 50 ft in supply well SW-19. The electrical measurements reveal three resistive layers. The upper layer (500 ohm-ft) corresponds to loosely compacted sands and gravels. The middle layer (675 ohm-ft) corresponds to compacted sands and gravels. The lower layer (175 ohm-ft) corresponds to a fresh water table assuming a drawn down in the borehole of 50 ft. The refraction survey reveals the same three interfaces, thus suggesting very strongly that the water table exists at about 400 ft depth with a draw down in the borehole of 50 ft. The reflection survey reveals a reflector at 400 ft depth in support of the resistivity and refraction models. Thus, all the models agree very well with the known data, assuming a 50 ft draw down cone in the borehole. Therefore, knowing all available geologic information, the geophysical assessment of groundwater potential at this site is very good.

T-14. With all available geologic information known, the geophysical assessment of groundwater potential at this site is very good. Knowing all available geologic information, the geophysical models (Figure 25) at this site correlate very well with the known data. The electrical measurements reveal four resistive layers. The upper two layers correspond to dry loosely compacted sands and gravels. The third layer (300 ohm-ft) corresponds to moist compacted sands and gravels, and the water table. The lowest layer (12 ohm-ft) corresponds to saline groundwater. The refraction survey reveals three acoustic layers. The upper layer (1500 ft/s) corresponds to dry loosely compacted sands and gravels. The middle layer (2500 ft/s) corresponds to moist compacted sands and gravels. The lowest layer (6600 ft/s) corresponds to the saturated sequence of sand with silt and clay. The shear wave reflection survey reveals a reflector at 35 ft corresponding to moist compacted sands and gravels. The shear wave refraction survey reveals the same shallow layer. The shear wave energy apparently did not penetrate deep enough to detect the deeper layers. Even though the shear wave surveys were not effective the refraction and resistivity surveys were very sensitive to the water table. Therefore, with all available geologic information known, the geophysical assessment of groundwater potential at this site is very good.

2. Fort Carson, Colorado data

CSM-1. As before, examination of the T-X plot (Figure 19) reveals that laterally changing velocities exist in the subsurface, making a straightforward geophysical interpretation of the site impossible.

CSM-3. With all available geologic information known, the geophysical assessment of groundwater potential at this site is good. Knowing all available geologic information, the geophysical model (Figure 26) at this site correlates well with the known data. The upper layer (1300 ft/s) corresponds to the loosely compacted weathered layer. The lower layer (9700 ft/s) corresponds to the Dakota Sandstone aquifer. The geologic model depicting the depth of the Dakota Sandstone at 10 ft is probably inaccurate as the rugged surface topography in the area was estimated from a 20 ft contour interval topographic map and the top of the Dakota Sandstone was projected based on the known depth 1/2 mile east and a regional dip value of about 330 ft/mile. Thus, the refraction model is probably quite accurate. Therefore, knowing all available geologic information, the geophysical assessment of groundwater potential at this site is good.

CSM-2. With all available geologic information known, the geophysical assessment of groundwater potential at this site is good. Knowing all available geologic information, the geophysical models (Figure 27) correlate fairly well to the known data. The electrical measurements reveal five resistive layers. The uppermost layer (490 ohm-ft) corresponds to the dry surface soil layer. The next layer (130 ohm-ft) corresponds to the moist weathered layer. The third layer (190 ohm-ft) corresponds to the shale layer. The fourth layer (55 ohm-ft) corresponds to the Dakota Sandstone aquifer. The bottom layer (180 ohm-ft) probably corresponds to a lower porosity zone in the Dakota Sandstone. The refraction survey reveals three acoustical layers. The upper layer (1900 ft/s) corresponds to the weathered layer. The middle layer (5500 ft/s) corresponds to the shale layer. The lower layer (10,000 ft/s) probably corresponds to the Dakota Sandstone. Although the Dakota Sandstone is apparently shallower (65 ft) than what the refraction survey would seem to indicate (85 ft), in consideration of the uncertainty of the actual depth to the Dakota Sandstone at this location, this model is in fair agreement with known information. Therefore, knowing all available geologic information, the geophysical assessment of groundwater potential at this site is good.

EVALUATION

Field Methodology

A. Seismic refraction/reflection

For refraction shooting, the largest shotpoint to geophone offset should be at least five times the desired depth of investigation.

The decision to use seismic reflection in addition to refraction should be made before entering the field, as the time and cost of collecting useful reflection data are greater than for shooting a straight refraction survey. The field procedure for collecting refraction data is comprehensively covered in a previous report (Applegate, et al, 1982); however, if the data is to be processed for reflection information, then the following field considerations are necessary to raise data quality and lower processing time and complexity.

1. Remain consistent. Ideally, the survey parameters are set, and the shooting pattern decided, before any data is collected. Occasionally the incoming data will mandate a parameter change while in the field, but this should be done cautiously.

2. The source must be repeatable and contain good high frequency energy. Possible choices include an explosive in the air on a two-foot long stake, or a gun fired into the ground. Buried explosives contain the necessary energy, but are time-consuming.

3. Shoot at least every third or fourth geophone station. For seismic reflection, the normal moveout equation breaks down when the source to receiver offset is greater than twice the depth of investigation. This means a reflector twenty feet deep can only be recovered from the traces recorded by geophones within forty feet of the shot. An example shooting pattern (assuming a twelve channel seismograph and a three spread survey 825 feet long with 25 feet between stations) would be to first locate and flag all 34 stations, put the live geophone traces 1-12 at stations 1-12, and then shoot stations 1, 5, 8, 12, 16, 19, 23, 27, 30, and 34. Next, move the live traces 1-12 to station numbers 12-23 and again shoot at the above ten stations. Move the live traces to stations 23-34, and shoot the ten stations again to complete the survey.

4. Avoid drastic filtering of field data. The signal frequencies of interest for shallow seismic reflection generally range from 60 Hz to 500 Hz. Consequently, a hi-cut filter set below 60-80 Hz can destroy most of the useful signal and should be avoided.

5. Use conservative gains. The electronics of the recording instrument limit the size of the number (amplitude) held in memory. A high gain will cause this number to be recorded repeatedly, and acts as a hi-cut filter. Low gains can almost always be recovered in the computer.

6. Keep field procedures within data processing capabilities. A fast, efficient interpretation of field data is best accomplished if the field methodology and the processing package are designed together. The use of field portable, shallow application seismographs to collect reflection data is relatively new, and data processing on field portable microcomputers is limited. The capabilities and limitations of the specific package should be understood before the field effort is begun.

B. Shear Source

Refracted seismic arrivals from a shear wave source are generally very weak, however, reflected seismic arrivals can be useful in groundwater detection. The field methodology differs only in the use of a shear wave source, and possibly a change in the shooting pattern to enhance the coverage.

C. Resistivity

Vertical resistivity soundings (Schlumberger soundings) were employed to measure the vertical variation of electrical resistivity with depth. In order to detect groundwater, an

adequate sampling rate is necessary. This allows an accurate modeling of the resistivities. During this study, six to ten measurements per decade of electrode spacing were used equally spaced on a logarithmic scale (e.g. 10, 14, 20, 30, 50, 70, 100, etc.). This sampling rate proved to be inadequate to accurately model the resistivities. An adequate sampling rate would be a minimum of eighteen measurements per decade if equally spaced on a logarithmic scale (e.g. 10, 11.5, 13, 15, 17, 19, 22, 25, 28, 32, 36, 41, 46, 52, 60, 68, 78, 88, 100, etc.). Also, the sounding should be carried out to a spacing of at least four times the desired depth of investigation.

Field Equipment

The field equipment used to gather all the refraction and reflection data is both rugged and mobile (Figure 28). It consists of a multichannel seismograph, seismic sources, geophones, and seismic cables (Applegate, et al, 1982). A digital magnetic tape recorder (Figure 29) was also used to record seismic events for later data processing on a microcomputer. The field equipment used to gather the electrical measurements is also rugged and mobile (Figure 30). It consists of a power supply, a sophisticated multimeter, four stainless steel stakes, and several thousand ft of wire. All of the seismic and electrical field equipment is relatively inexpensive and available "off-the-shelf".

Interpretation Methodology

A. Seismic refraction

A detailed explanation of refraction interpretation appears in an earlier report (see Applegate, et al, 1982). Examination of Table 4 indicates that as more subsurface information was available, the confidence level increased. This is expected. There may be occasions where the ARMY has no geologic information for a given site. The corresponding confidence levels in Table 4 will be typical for the ARMY as well. Most of the time, the ARMY will have a limited supply of geologic information for a given site and the corresponding confidence levels in Table 4 should be expected. Occasionally the ARMY will have access to large supplies of geologic information for a given site and the corresponding confidence levels in Table 4 will be typical.

TABLE 4

Summary of Confidence Levels

Site	No Information	Some Information	All Available
HTA-1	Fair to Good	Good	Good
MAR-2	Fair to Good	Good	Good
SW-19	Good	Very Good	Very Good
T-14	Good	Very Good	Very Good
CSM-3	Fair	Good	Good
CSM-2	Fair	Fair to Good	Good

B. Seismic reflection

Seismic reflection interpretation, and the data processing that precedes it, are topics which support international industries. Countless textbooks and technical papers are available which describe these wide-embracing and detailed subjects. The following paragraphs will briefly introduce the theory, explain the basic processing steps, and discuss the approach to interpreting the resulting profile.

1. Theory

Seismic energy is reflected back to the surface whenever a wave encounters a change in the velocity and density of the medium through which it is propagating. It is usually assumed that each reflected event is coming from a point in the subsurface directly beneath the mid-point between the source and receiver. Different source-receiver combinations can share the same mid-point although their offset distances vary (Figure 31). These common mid-points are referred to as CDP's or common depth points. The number of source-receiver combinations that belong to the same CDP is referred to as the fold coverage. The relationship between the source to receiver offset distance and the arrival time from a reflecting horizon is expressed by the normal moveout equation. For a simple two layer case it is

$$T^2 = \frac{x^2}{v_1^2} + \frac{4z^2}{v_1^2} \qquad (6)$$

where T is the arrival time, x is the offset distance, z is the depth to the reflecting horizon, and v_1 is the velocity of the upper layer. This is a hyperbolic equation which concludes that the reflected arrivals will appear on the shot record as a hyperbolic arc tangential to the direct arrival (Figure 32). However, most reflections are less than 1% of the incident energy and resolution of the reflectors is dependent on the frequency of the energy wave, which is most directly related to its distance from the source. A good rule of thumb states that the energy is halved with every period of time. Thus, at a speed of 2000 ft/s a 100 Hz wavelet has lost one-half of its energy in 20 feet of travel; whereas, at the same speed, a 20 Hz wavelet can travel 100 feet before being reduced to half its original energy. These facts underscore the need for signal enhancement if reflections are to be recovered, especially if the survey calls for shallow, high resolution interpretations. In general, the reflections are weaker than the noise and data processing techniques must be employed to raise the signal to noise ratio.

2. Basic processing procedures

The simplest reflection processing and interpretation would involve identifying the reflections on the shot record, calculating the velocity from a hand plot of T^2 vs. x^2, and solving for the depth to the reflector.

Unfortunately, the inability to identify the reflections on a raw shot record and the time consumption of hand measurements, plots, and calculations make this procedure impractical. However, it does illustrate the heart of any reflection processing package, which is velocity determination and normal moveout correction. All other steps are related to overcoming specific noise problems or providing simple signal-to-noise ratio enhancement. A practical computer processing description follows:

a. CDP sort

Once the data is in the computer it is sorted such that all traces belonging to the same CDP are located together and arranged from the first CDP to the last. This program demands access to all the data and requires a large disk or memory storage capability. Its length and complexity are directly related to the field shooting pattern.

b. Spherical divergence gain recovery

This is a simple, one-time process that amplifies the late-time events within a given trace according to the mathematics of spherical divergence. Originally, events recorded late in time have traveled farther than early events and are weaker in amplitude.

c. Frequency filter

Usually a shallow reflected event reaches the geophone at the same time as the groundroll (surface waves) or airblast (air wave), and it cannot be seen

because it is much smaller in amplitude. Also, if the geophone is planted poorly, the cable is bad, or the source is weak relative to the background noise (traffic, power lines, pumping stations, etc.), then the reflections can be hard to see. Some of these noises have characteristic frequencies which can be filtered out. A simple, general filtering routine can be a useful tool when properly employed.

d. Mute

All seismic reflections are recorded after the first arrival, permitting the early portion of each trace to be zeroed to reduce any early noise.

e. Energy equalization

This is an often run subroutine that sets the total energy of each trace to the same level. It is necessary because the far offset traces receive much less energy than those next to the source. Before they can be stacked they must be equalized or they will not average evenly.

f. Static correction

Variable surface topography and differences in the thickness of the low velocity weathered zone can produce time shifts on individual geophones. This may or may not be a problem depending on the field site. The programs to correct static shifts vary

from highly complex to fairly basic, and often use the refraction interpretation procedure to make the calculations.

g. Deconvolution

For easier reflection recognition, this is a wavelet processing program based on the asssumption that the original source energy has a known shape that is altered by the earth. Given the before and after wavelet shapes, the program determines the earth filter and enhances it as a reflection if appropriate.

h. Velocity analysis

The use of the correct velocities is vital to the proper NMO (normal move-out) correction and subsequent stack. Usually the velocities are not known and must be determined by various computer procedures, most of which are dependent on a high signal-to-noise ratio and multiple fold coverage. The most common method is to perform the NMO correction and CDP stack at numerous velocities and pick the one that looks best.

i. NMO correction

Using the normal moveout equation and the best velocities, the hyperbolic curve of the reflected events is made horizontal. This is done by reading in the offset of each trace and re-creating the trace as if it had a zero offset. If the velocities are correct,

a given reflector will then appear at the same time on all traces of a particular common depth point.

j. CDP stack

Once the traces are corrected for normal moveout, a single trace is made from the straight average of all traces common to a given CDP.

k. Plot display

The plot display never performs a permanent process on any trace, but it is critical to the correct analization of the data as it goes through each of the above procedures.

3. Interpretation

In any seismic reflection interpretation, the uncertainties must be kept in mind. If the velocities are dubious, then all depths are dubious. The reflection section is still a time plot, and cannot be related to the subsurface geology without velocity information. In our shallow application search for groundwater, our shooting pattern was purposely designed for refraction information with hopes of later recovering reflections from the data without creating major field methodology changes. It is apparent that this limited our velocity model to the refraction interpretation, which in turn limited the reflection interpretation to a reconnaissance tool for verifying or disputing the model. This handshaking of the two methods is important in providing higher confidence levels, but the reflection method can

be made more useful by shooting more stations to get enough fold coverage to develop a reflection stacking velocity function. This can in turn be combined with the refraction information to refine each model with the other. Shooting more stations (less distance between shot points) also gives more near surface information, and can enhance the refraction interpretation. Reflection interpretation is best used as a mapping tool to detail a horizon that is already understood. With no prior knowledge of the subsurface, the nature of an indicated horizon is uncertain even when its location can be determined. The reflection method obtains its full usefulness when used in conjunction with all borehole information, and other geophysical models.

C. Shear waves

With shear waves, the interpreter will compare the velocity ratio of compressional waves to shear waves (Vp/Vs). An increase in the Vp/Vs ratio is indicative of an increase in water content in rock.

D. Resistivity

A detailed explanation of DC resistivity interpretation appears in an earlier report (see Applegate, et al, 1982). Under favorable conditions, the water table will be detected as a less resistive layer (1 to 100 ohm-ft). At the fresh-saline water interface, the resistivity of the saline (brackish) water will be less (1 to 30 ohm-ft). Clays can

hinder the detection of the water table, because their resistivities can be very similar to the resistivities of saturated sediments.

COMPUTER SOFTWARE

Assessment

Computer software exists for both seismic and electrical interpretation, however, it is not user-friendly and requires expertise to make competent interpretations. Much of the software will run only on large mainframe computers. Very little user-friendly software exists for small mobile microcomputers.

Adaptation

It was an objective of this study to take existing software which were written for large mainframe computers, or written for microcomputers in a user-unfriendly way, and adapt the software to run in BASIC language on an IBM PC microcomputer in a user-friendly fashion.

Development

User-friendly refraction processing and interpretation software was developed to process and interpret all the field data collected during this study. This was a very encouraging part of the study, as programs were written to carry the user along from one step to the next (see Figures 33-36). Throughout the program, helpful advice was written in plain english in such a way that the user would not have to read a lengthy manual in order to run the programs. User-friendly reflection processing software was not completely developed, but did reach a very encouraging

stage. Further development is needed to enhance the user-friendliness of the developed software, so that it may approach the "black box" concept. This would lead to artificial intelligence software which could make decisions in confidence levels as to the presence and depth of groundwater, thereby nearing the goal of the "black box" concept.

CONCLUSIONS

Assessment of Integrated Methodologies

1. With no prior knowledge of geology, the integrated survey of seismic and electrical methods (described in this report) yielded fair to good confidence levels as to the presence and depth of groundwater.

2. With some knowledge of the geology, the integrated survey yielded fair to very good confidence levels.

3. With all available geologic information known, the integrated survey yielded good to very good confidence levels as to the presence and depth of groundwater.

4. The governing factors which affected confidence levels from fair to good, etc., were the following:

   a. For cases where the water table occurred in coarse-grained sediments (sands and gravels), the groundwater assessment was very successful.

   b. For cases where the water table occurred in fine-grained sediments (silts, clays, silty clays, sandy clays, etc.) the groundwater assessment proved to be not as straightforward.

   c. For cases where there existed a fresh-saline groundwater interface, the resistivity method revealed this fresh-saline interface.

d. For cases where there existed large topographic variations and complex geology, such as at the Fort Carson, Colorado site, the groundwater assessment proved to be difficult.

5. With a three-man crew, one can expect to cover 1,000 ft of a seismic refraction profile per 10 hour day. The profile coverage will usually be four times the depth of investigation. For example, if one wishes a 500 ft depth of investigation, then the profile coverage would need to be about 2,000 ft which would require two 10 hour days to perform.

Recommendations

1. Further refinement of field methodologies of refraction, reflection and especially resistivity measurements are needed to enhance the integration of their data sets, thus enhancing their sensitivity in the detection and assessment of groundwater.
2. Further refinements are needed in field equipment to make the integrated survey more expedient and mobile.
3. Further development of user-friendly software (see section COMPUTER SOFTWARE) is needed to approach the "black box" concept of groundwater detection. This will include an "artificial intelligence" software development which will perform all necessary processing, interpretation, and a "computer-decision making" routine which allows assessment of groundwater potential by unskilled military personnel.

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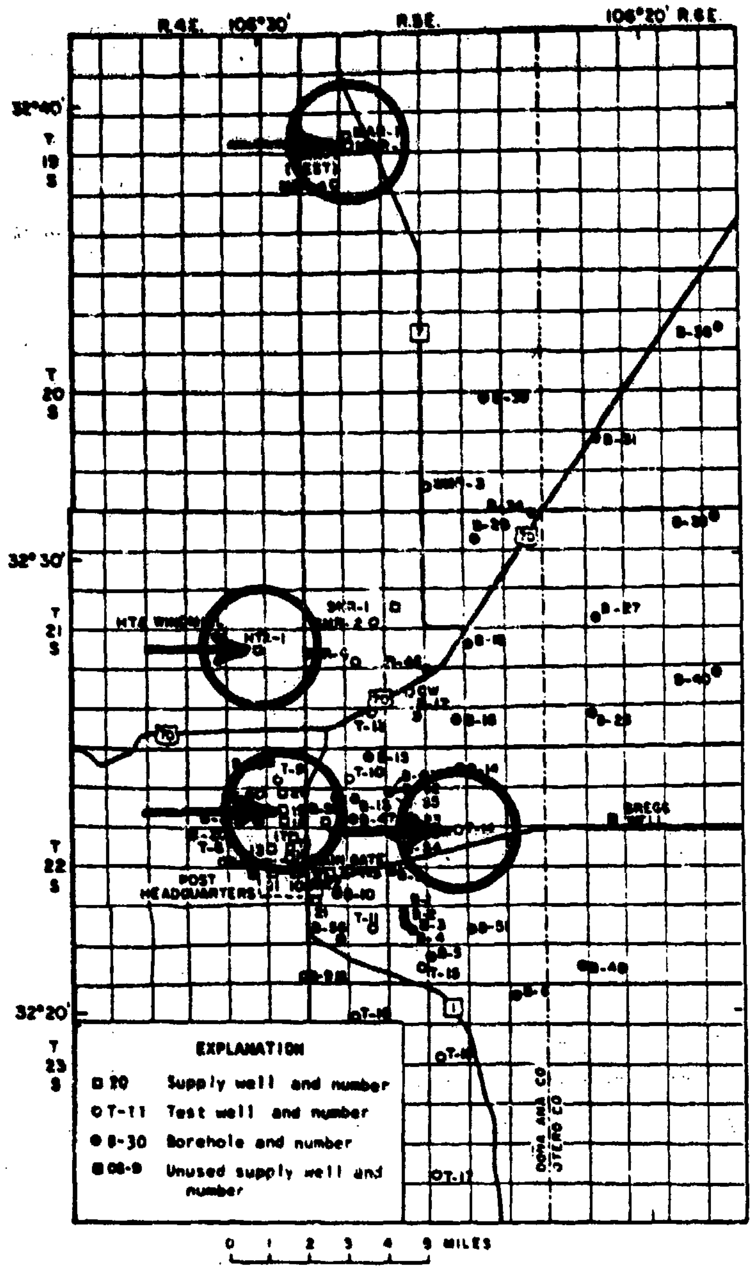

Figure 1. Location of supply and test wells used at White Sands, New Mexico. Adapted after Cruz (1981).

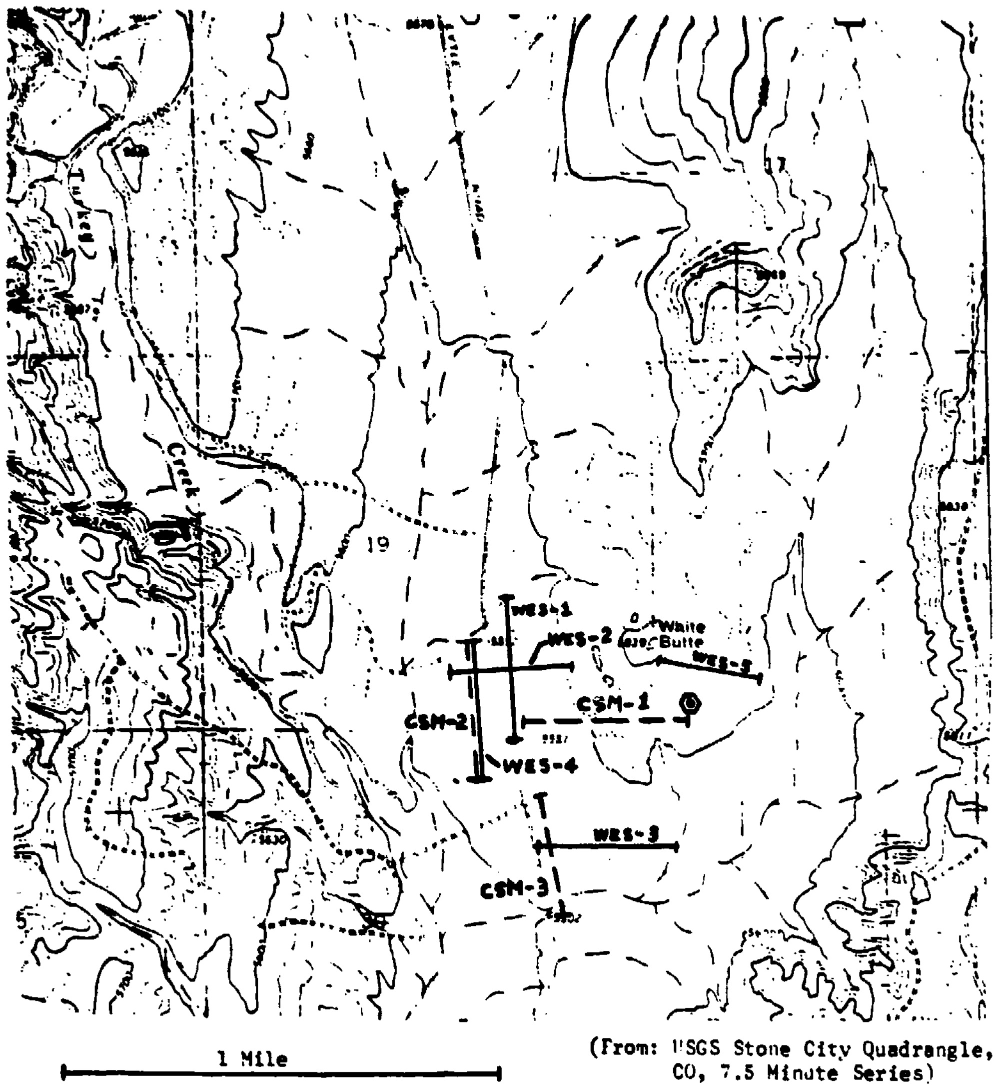

Figure 2. Survey layout, Fort Carson, Colorado. Adapted after USGS (1963).

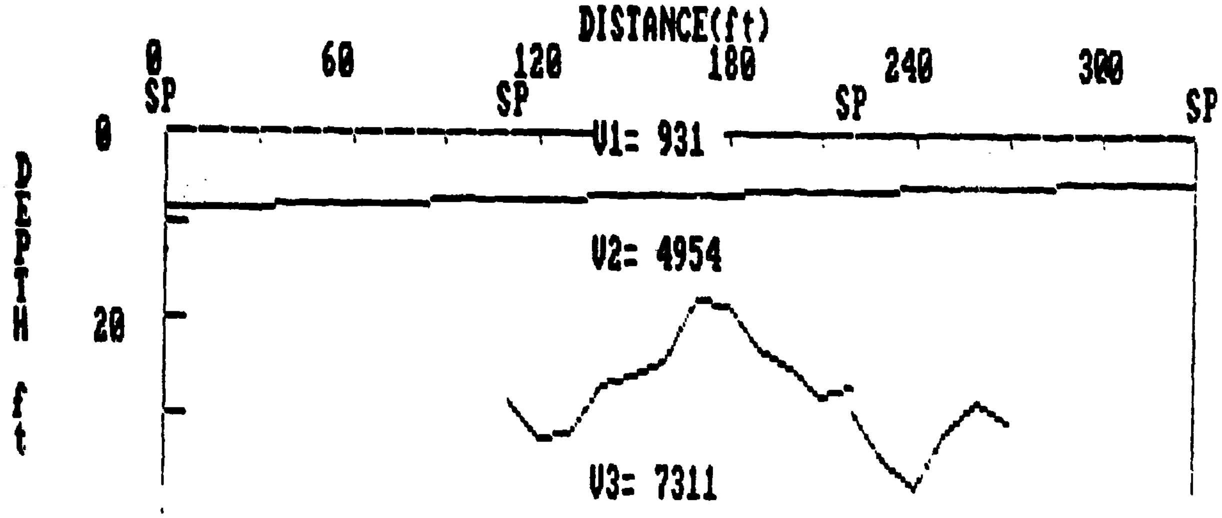

Figure 3. Computer-generated velocity model for HTA-1 line, White Sands, New Mexico. Velocities are in ft/s.

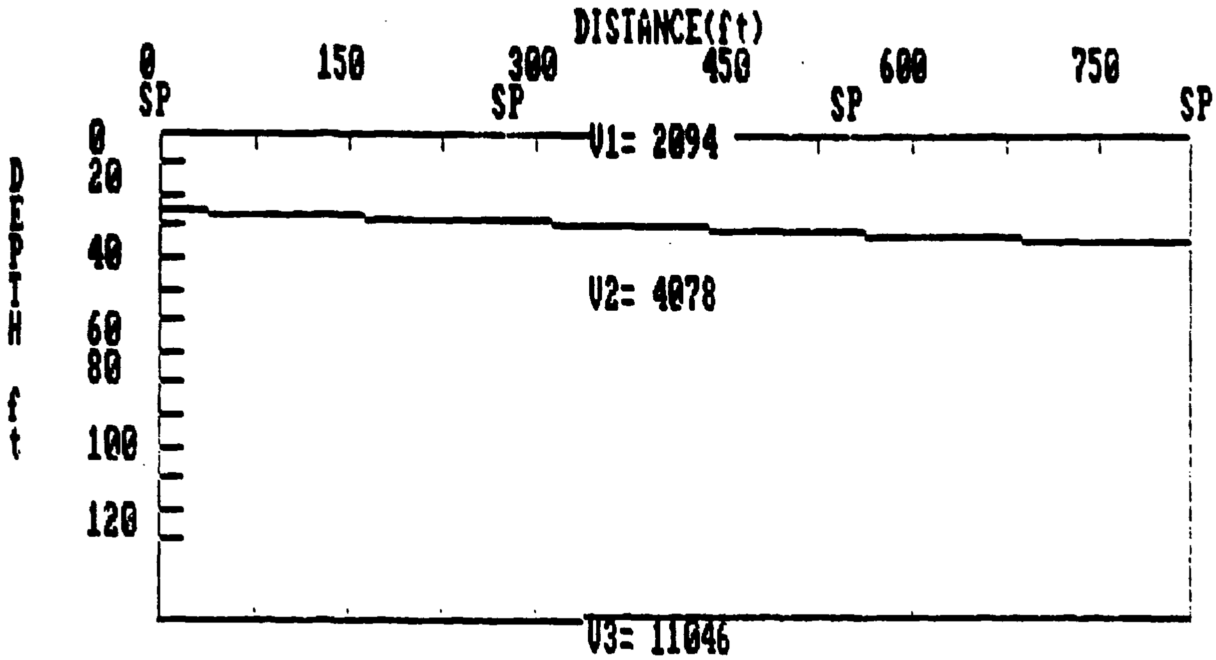

Figure 4. Computer-generated velocity model for MAR-2 line, White Sands, New Mexico. Velocities are in ft/s.

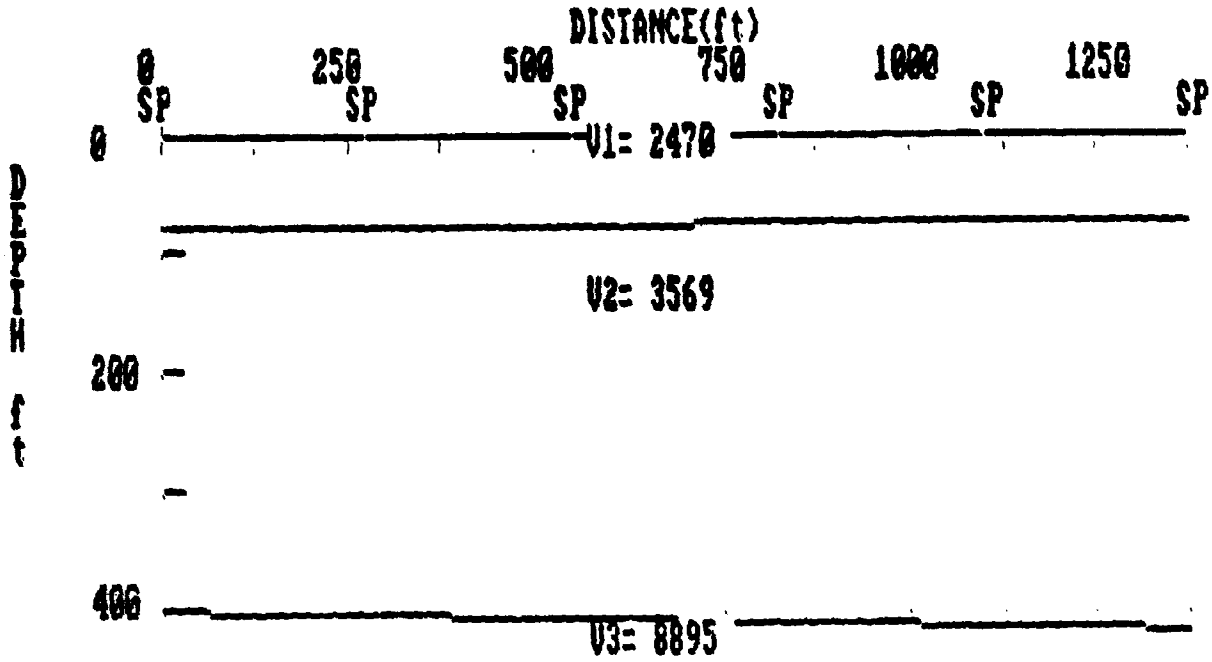

Figure 5. Computer-generated velocity model for SW-19 line, White Sands, New Mexico. Velocities are in ft/s.

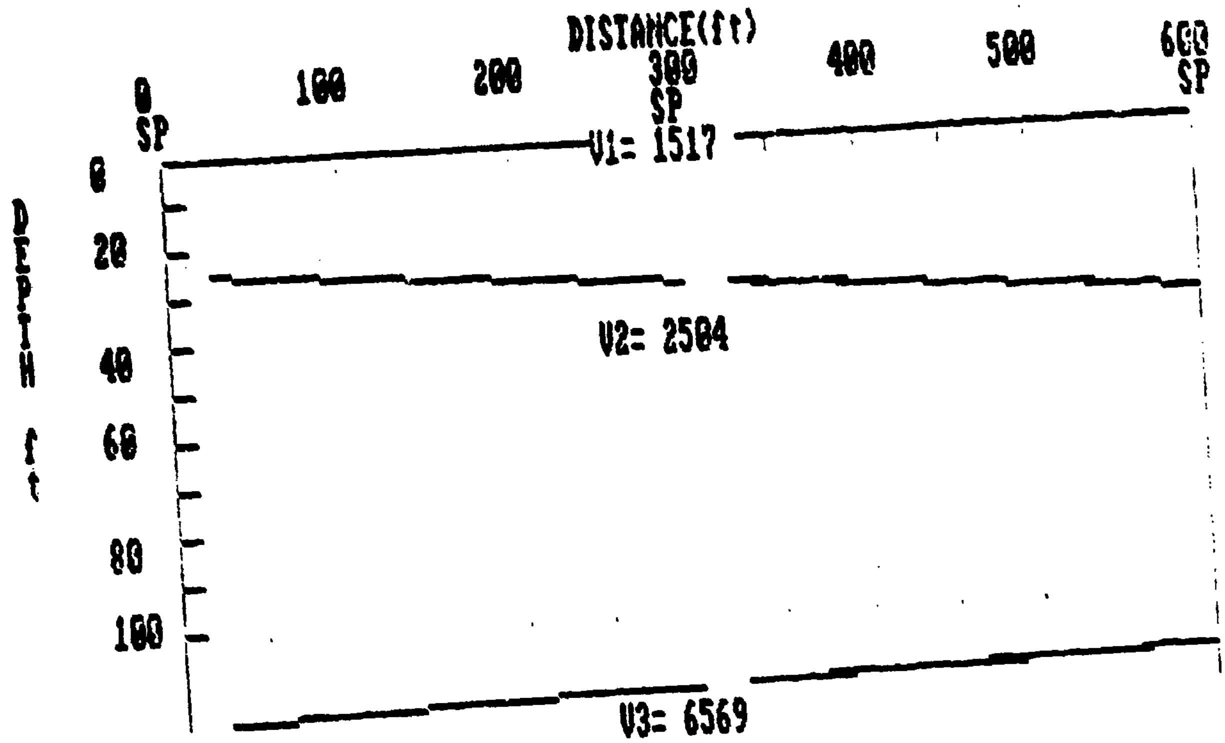

Figure 6. Computer-generated velocity model for T-14 line, White Sands, New Mexico. Velocities are in ft/s.

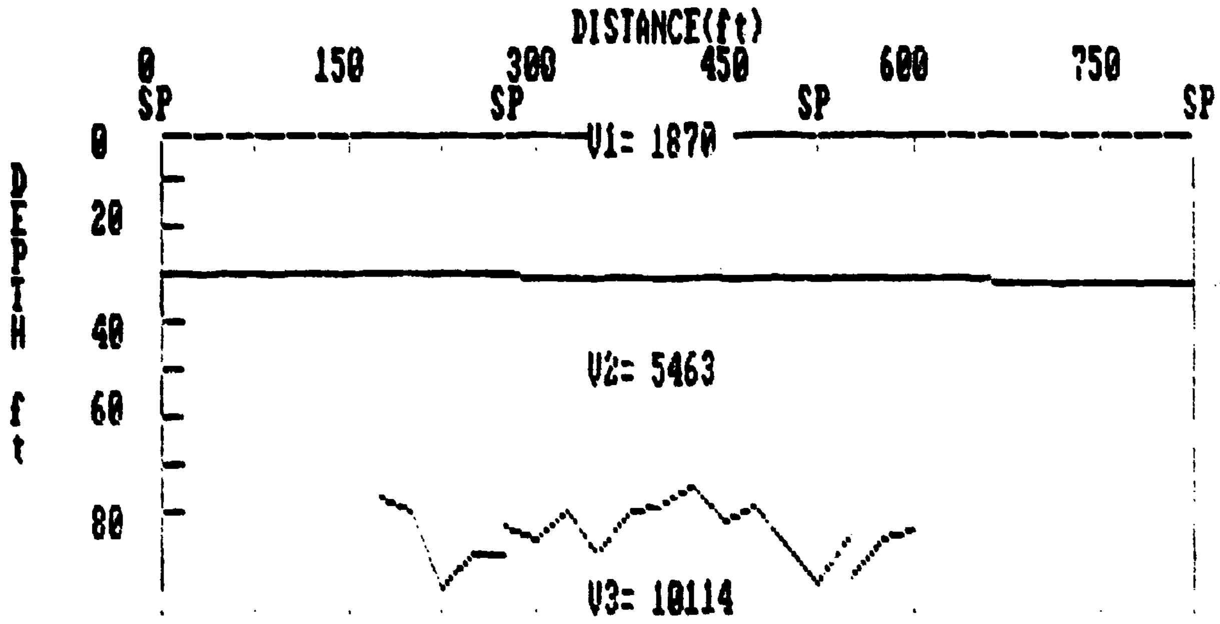

Figure 7. Computer-generated velocity model for CSM-2 line, Fort Carson, Colorado. Velocities are in ft/s.

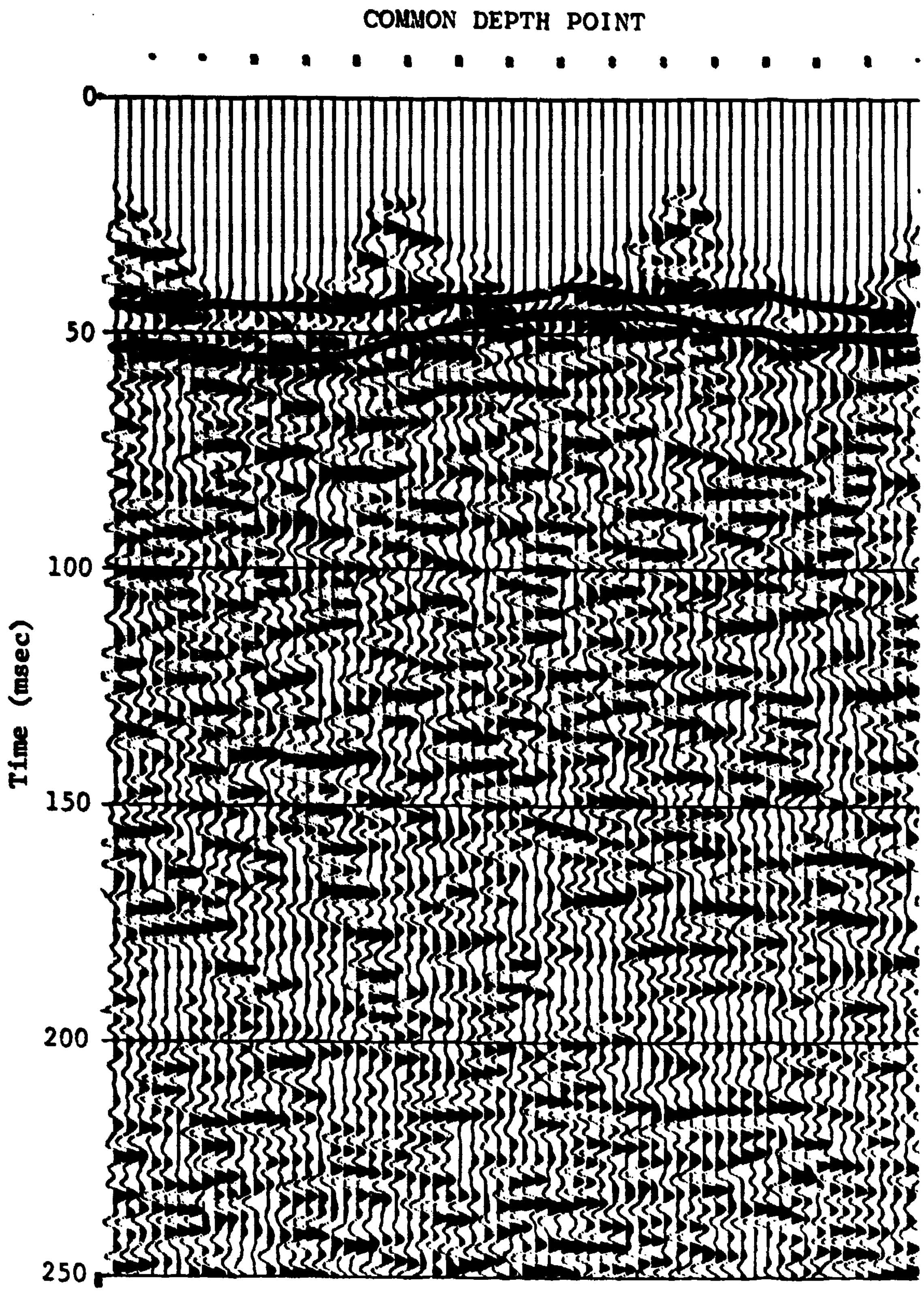

Figure 8. Reflection profile for HTA-1 line, White Sands, New Mexico.

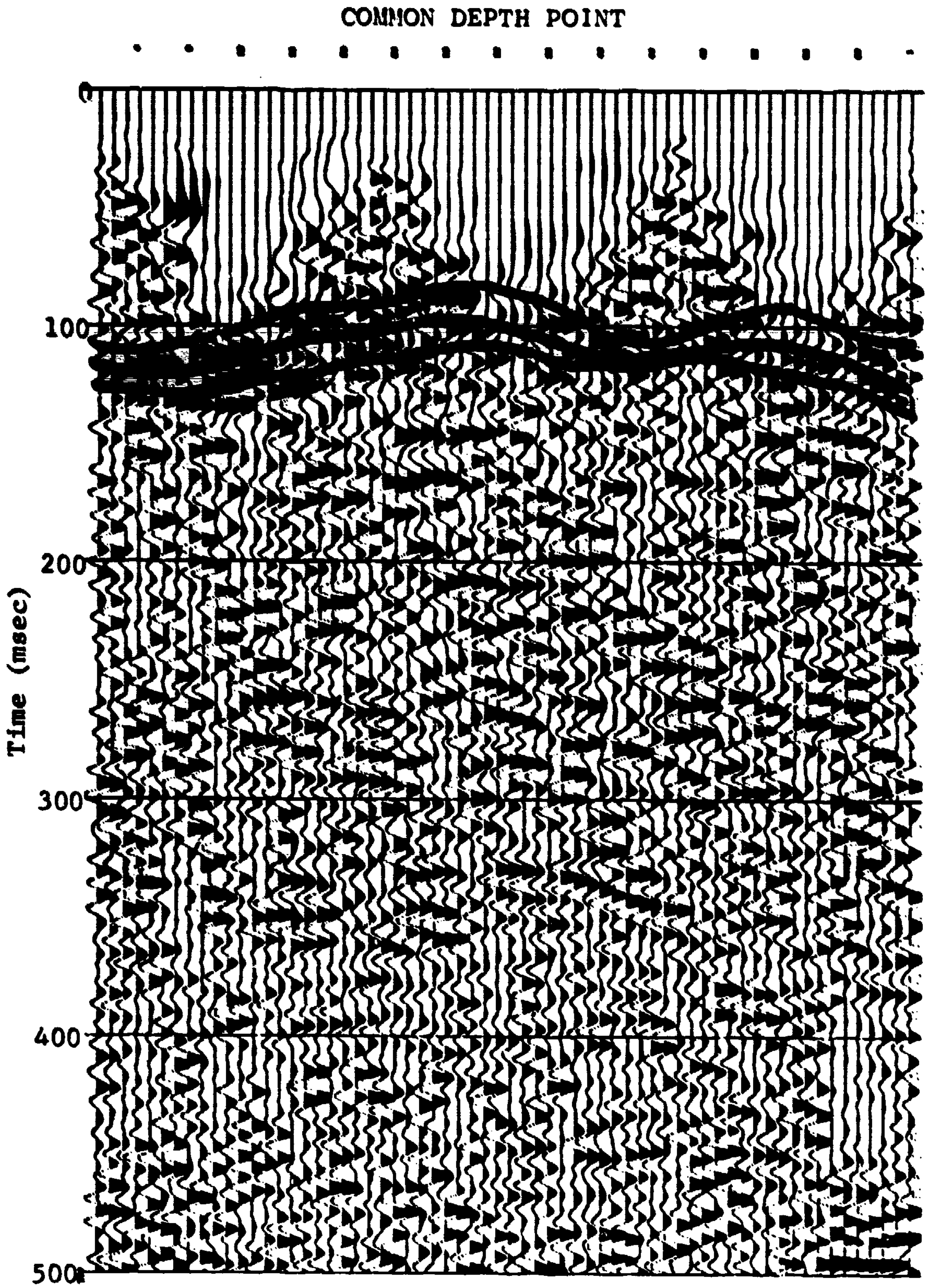

Figure 9. Reflection profile for MAR-2 line, White Sands, New Mexico.

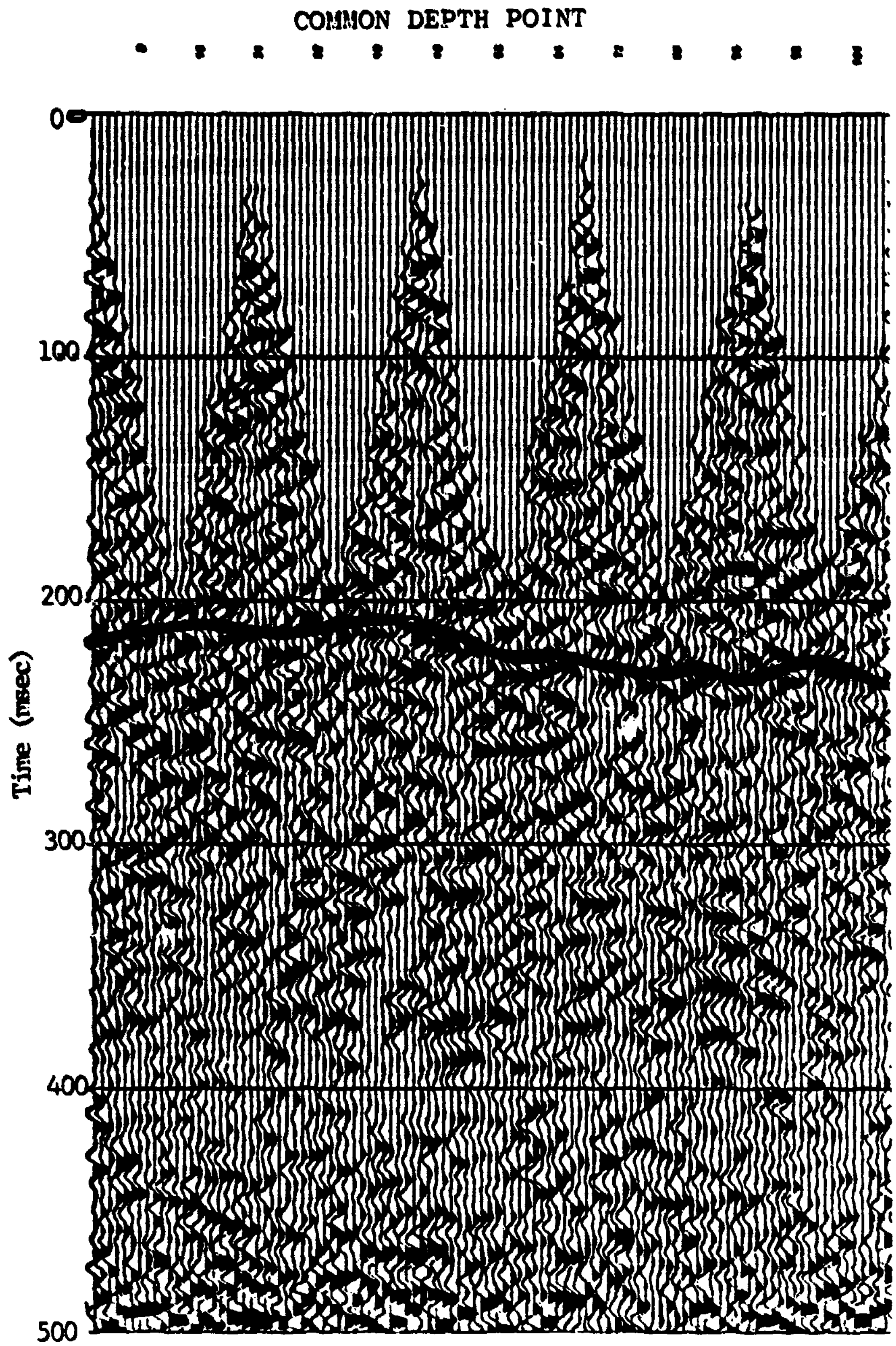

Figure 10. Reflection profile for SW-19 line, White Sands, New Mexico.

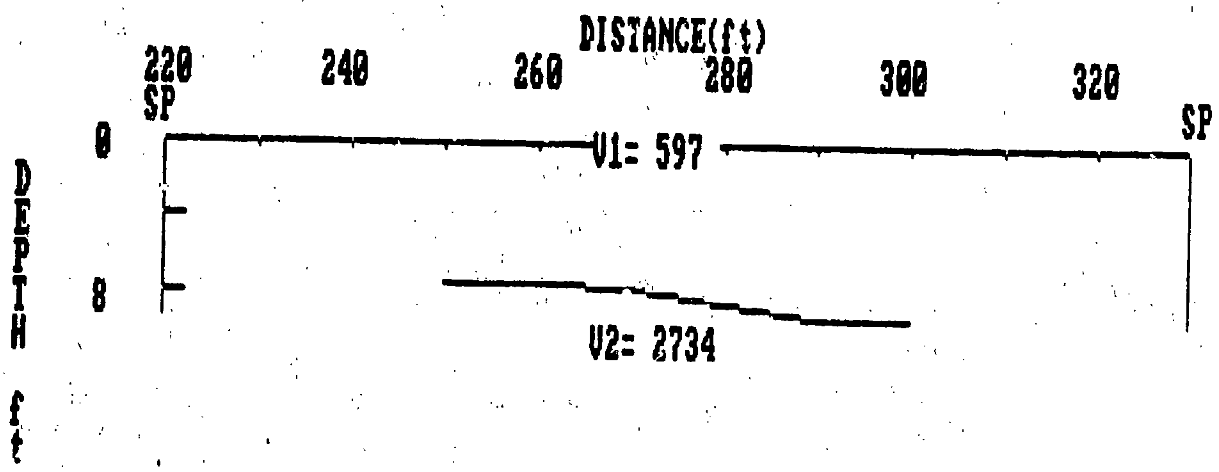

Figure 11. Computer-generated shear wave velocity model for HTA-1 line, White Sands, New Mexico. Velocities are in ft/s.

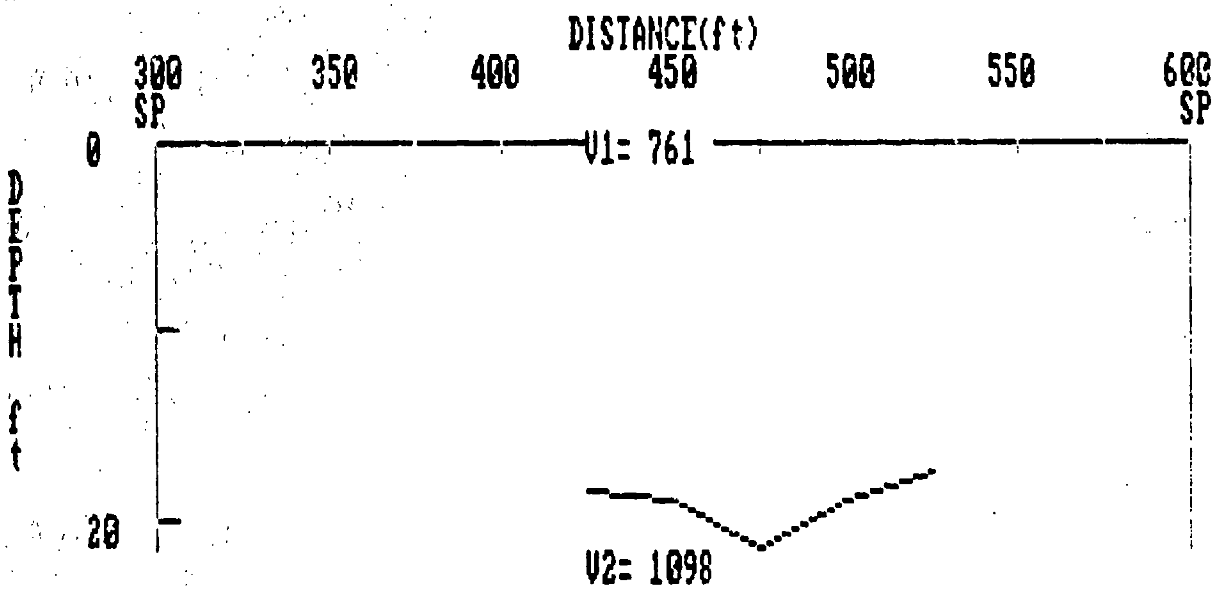

Figure 12. Computer-generated shear wave velocity model for T-14 line, White Sands, New Mexico. Velocities are in ft/s.

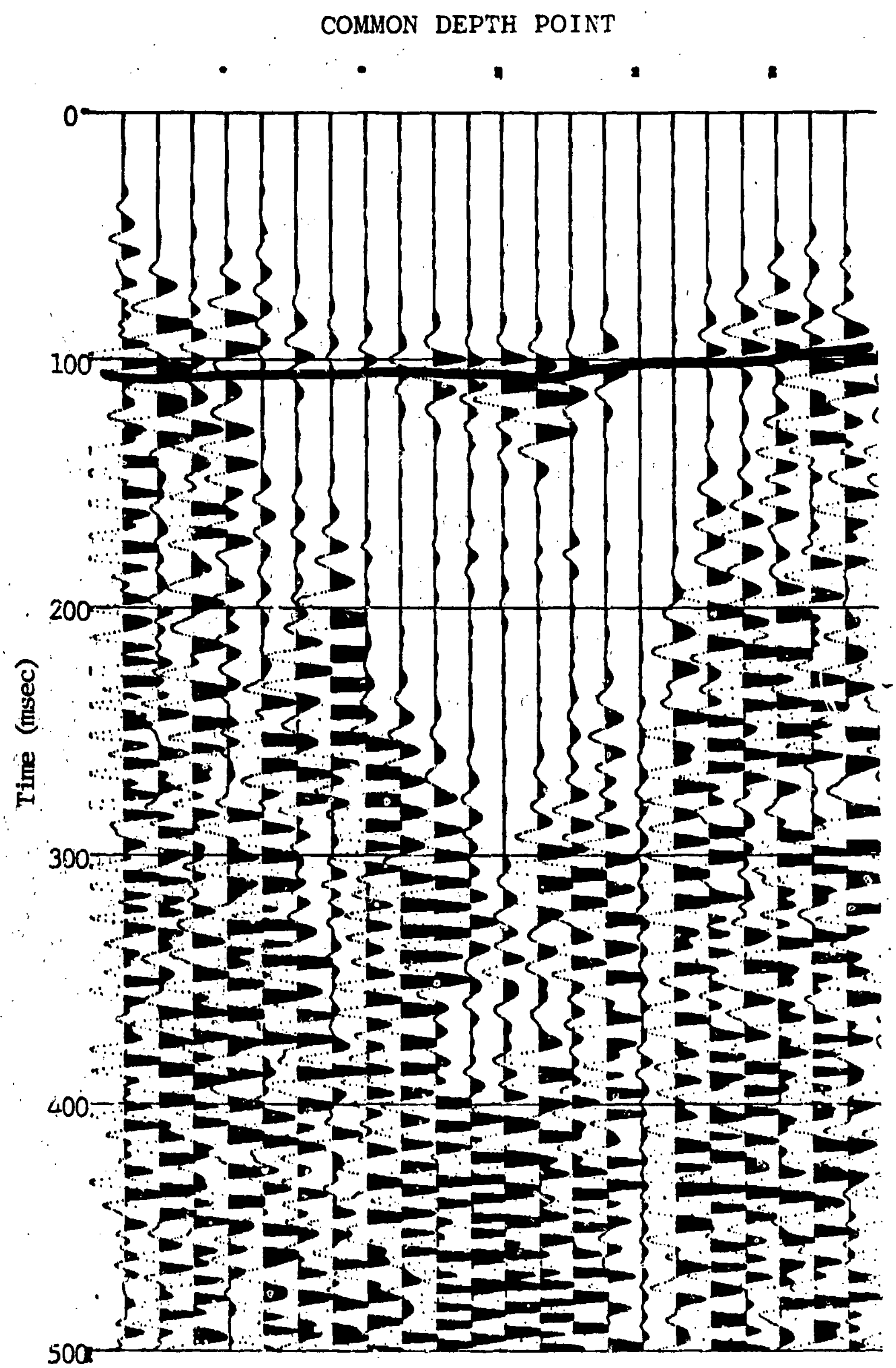

Figure 13. Shear wave reflection profile for T-14 line, White Sands, New Mexico.

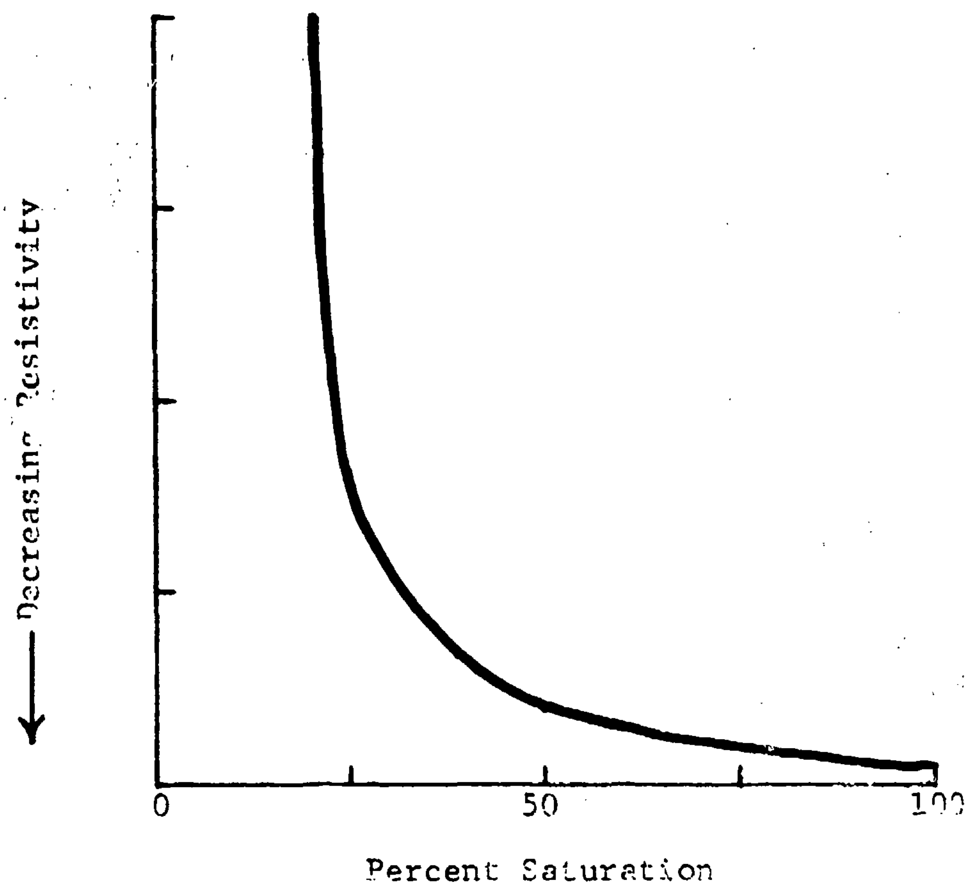

Figure 14. Resistivity variation with water saturation.

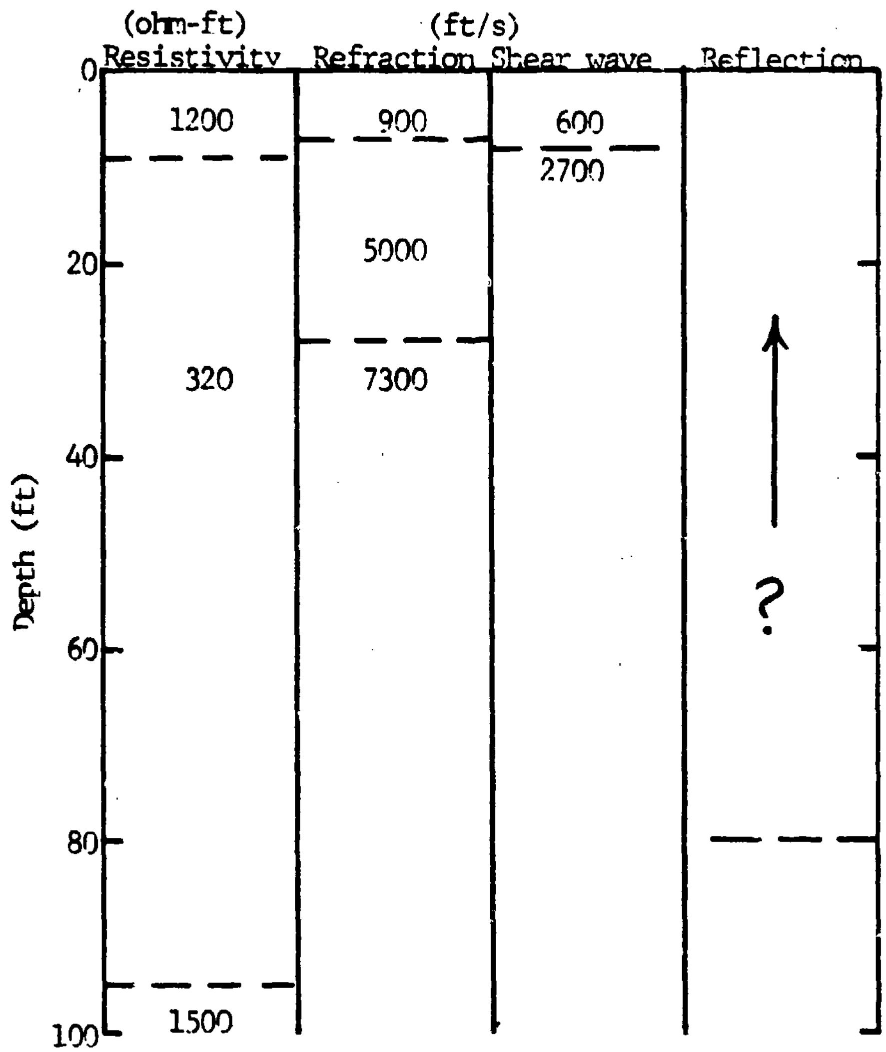

Figure 15. Geophysical models for HTA-1 line, White Sands, New Mexico.

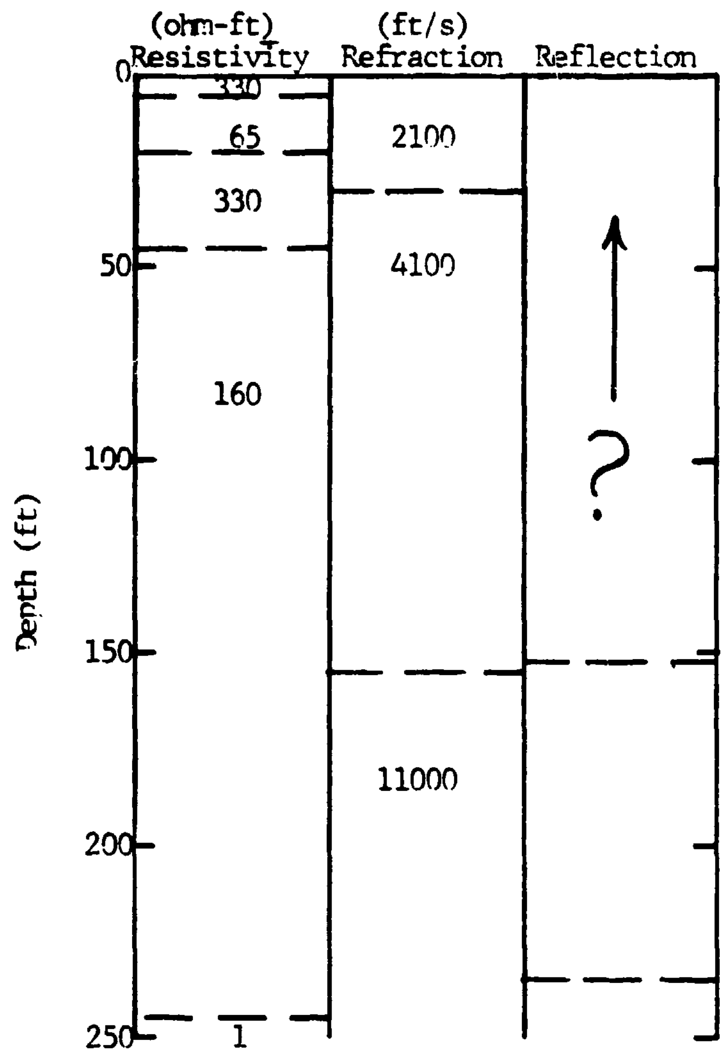

Figure 16. Geophysical models for MAR-2 line, White Sands, New Mexico.

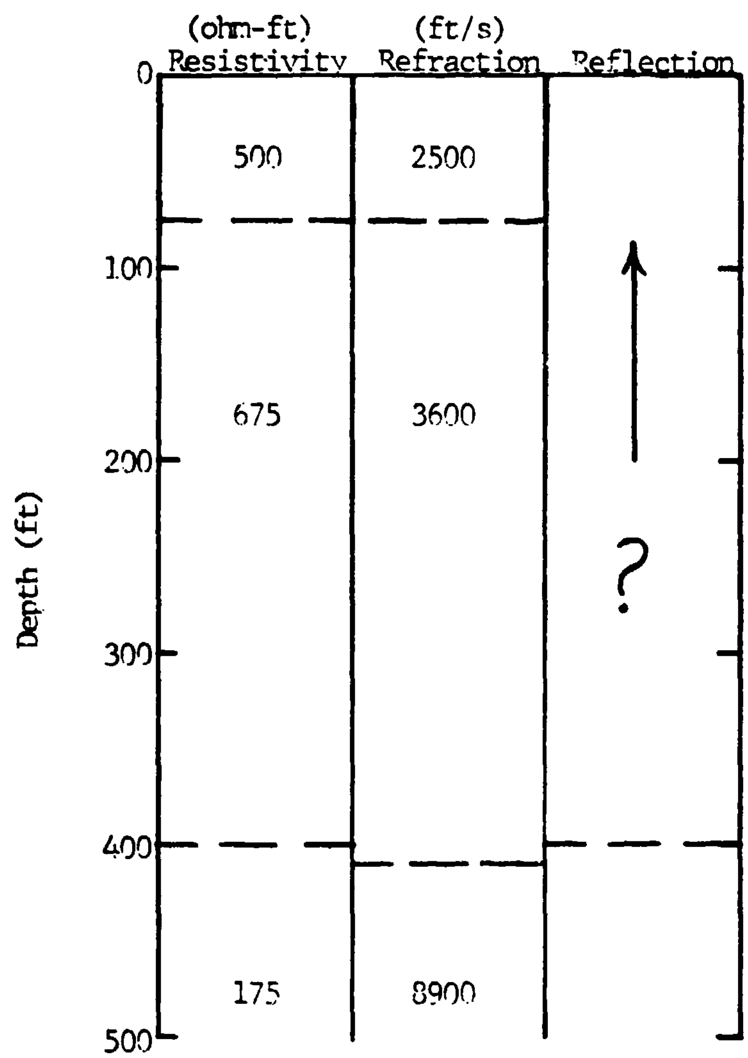

Figure 17. Geophysical models for SW-19 line, White Sands, New Mexico.

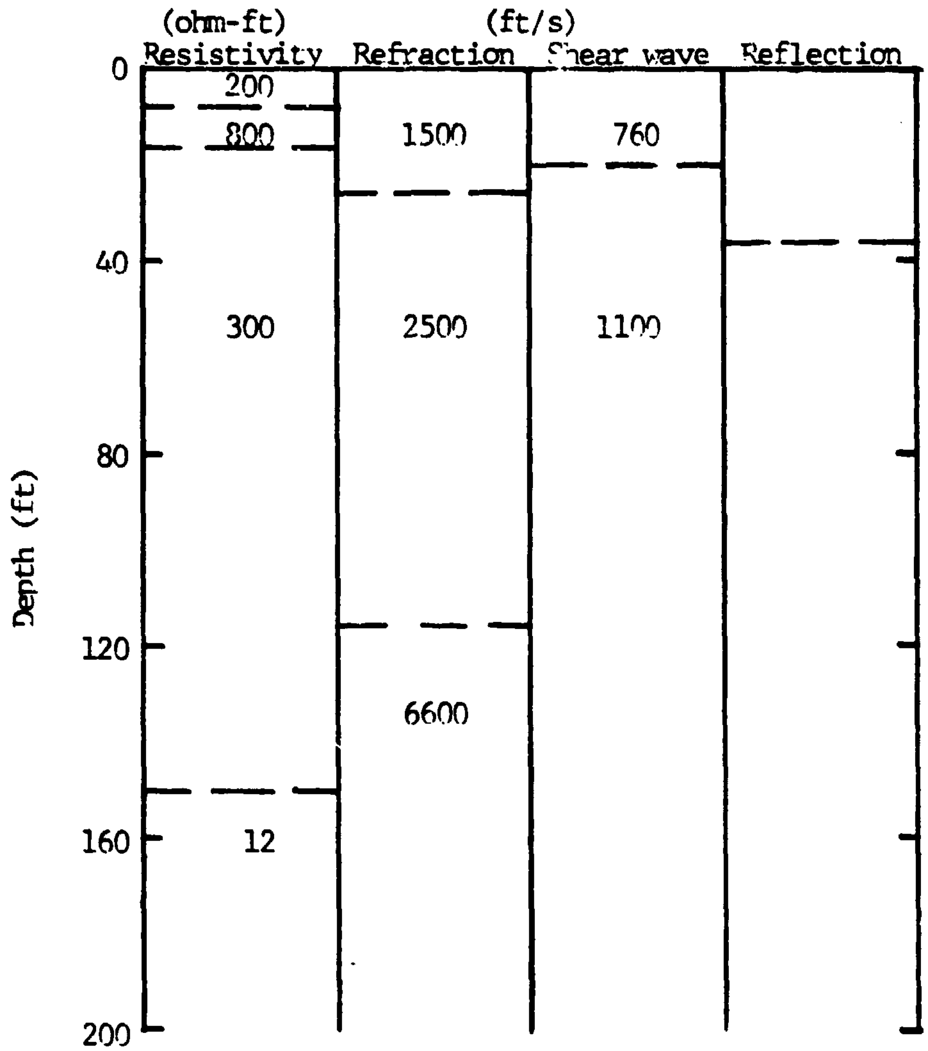

Figure 18. Geophysical models for T-14 line, White Sands, New Mexico.

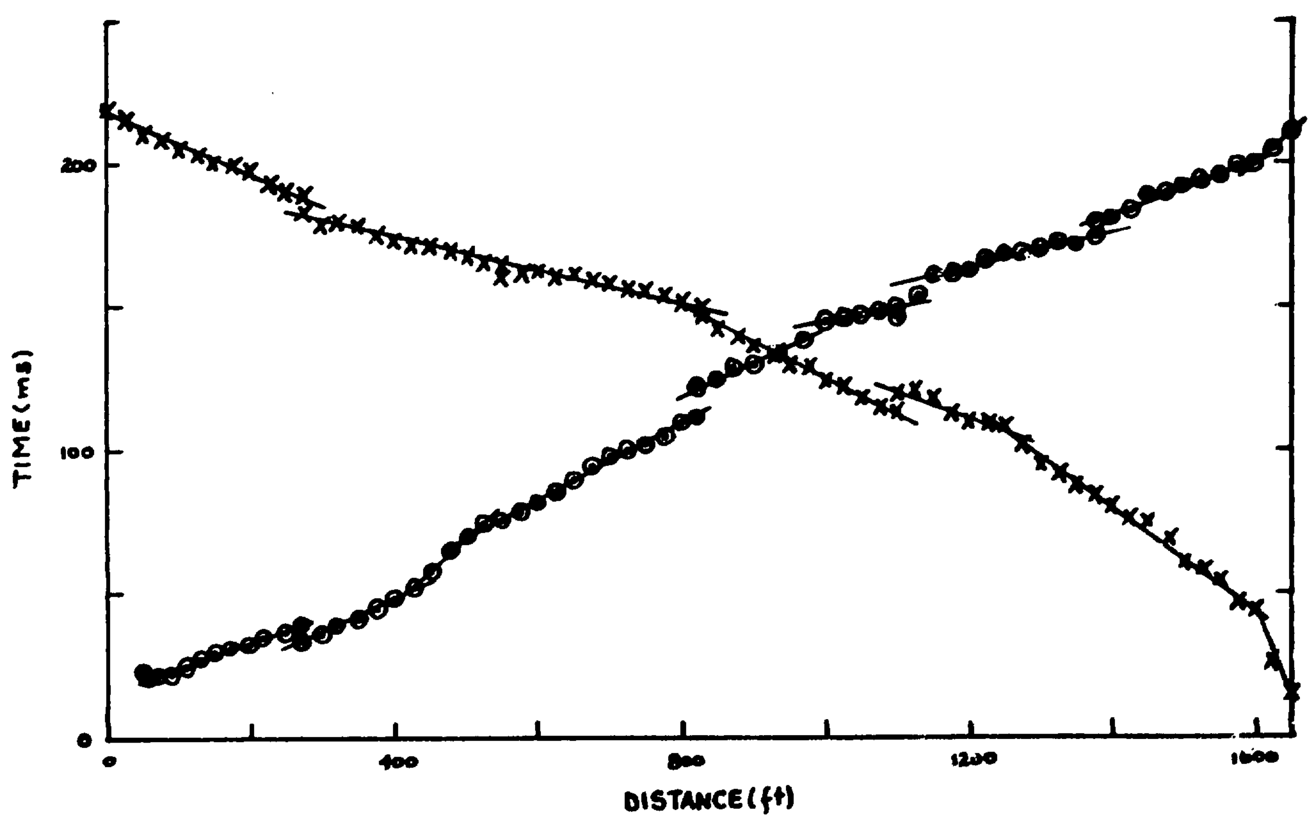

Figure 19. Time distance plot for CSM-1 line, Fort Carson, Colorado. Circles and crosses are the refracted arrival times.

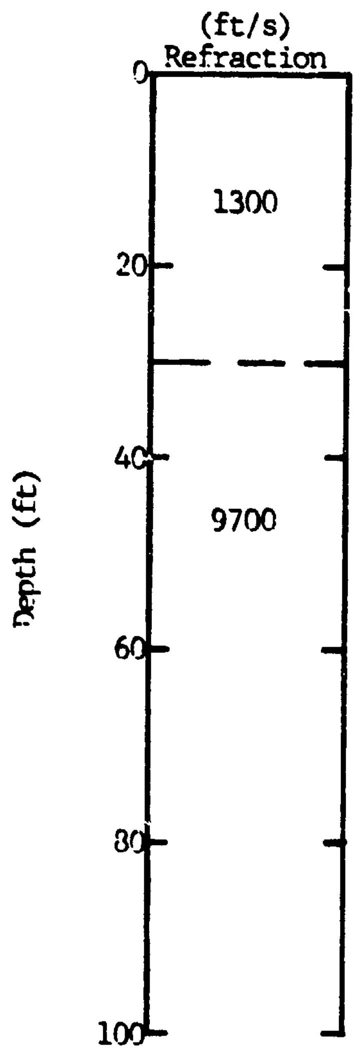

Figure 20. Geophysical model for CSM-3 line, Fort Carson, Colorado.

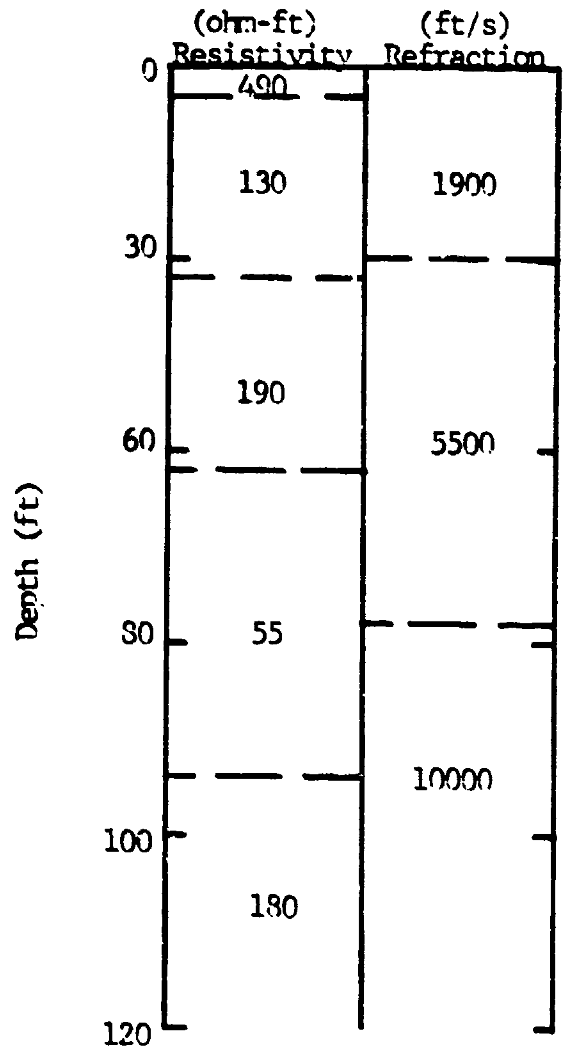

Figure 21. Geophysical models for CSM-2 and VES-4 line, Fort Carson, Colorado.

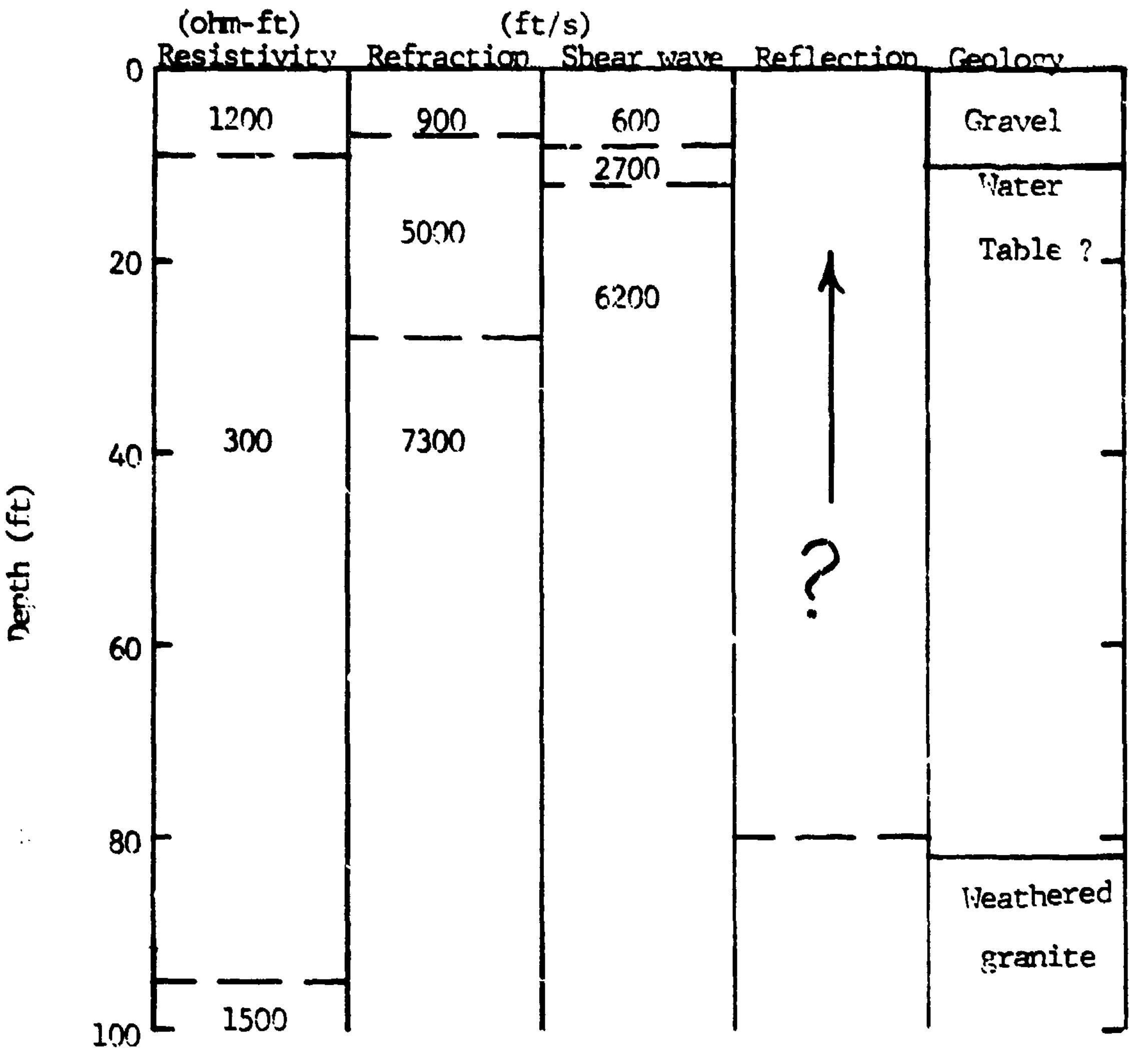

Figure 22. Geophysical and geological models for HTA-1 line, White Sands, New Mexico.

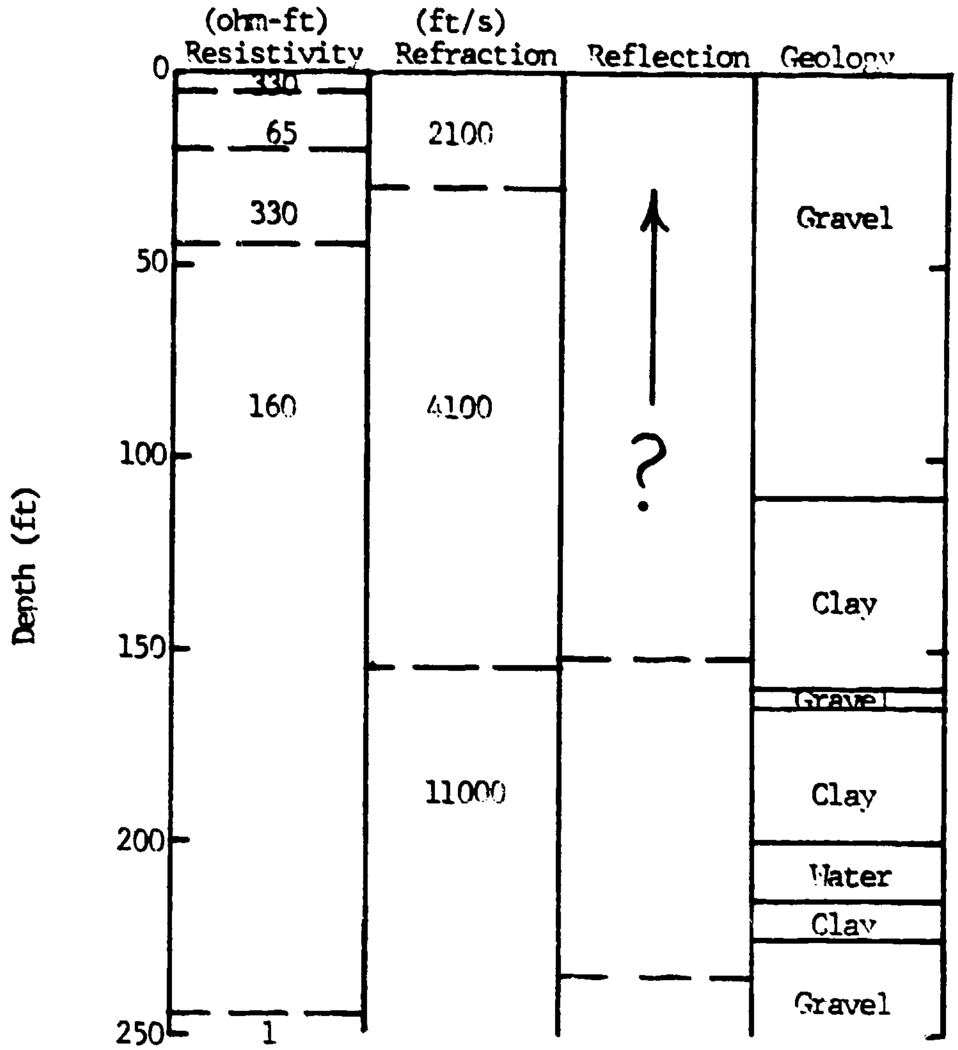

Figure 23. Geophysical and geological models for MAR-2 line, White Sands, New Mexico.

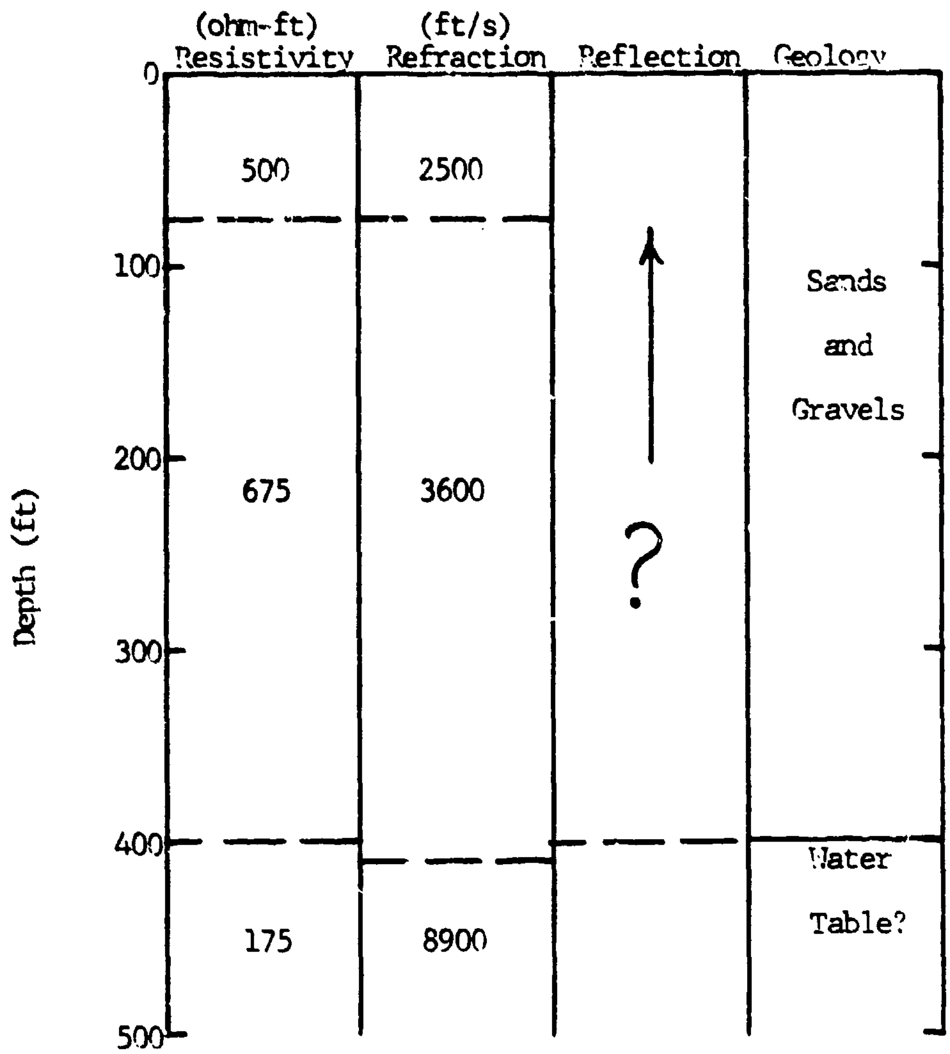

Figure 24. Geophysical and geological models for SW-19 line, White Sands, New Mexico.

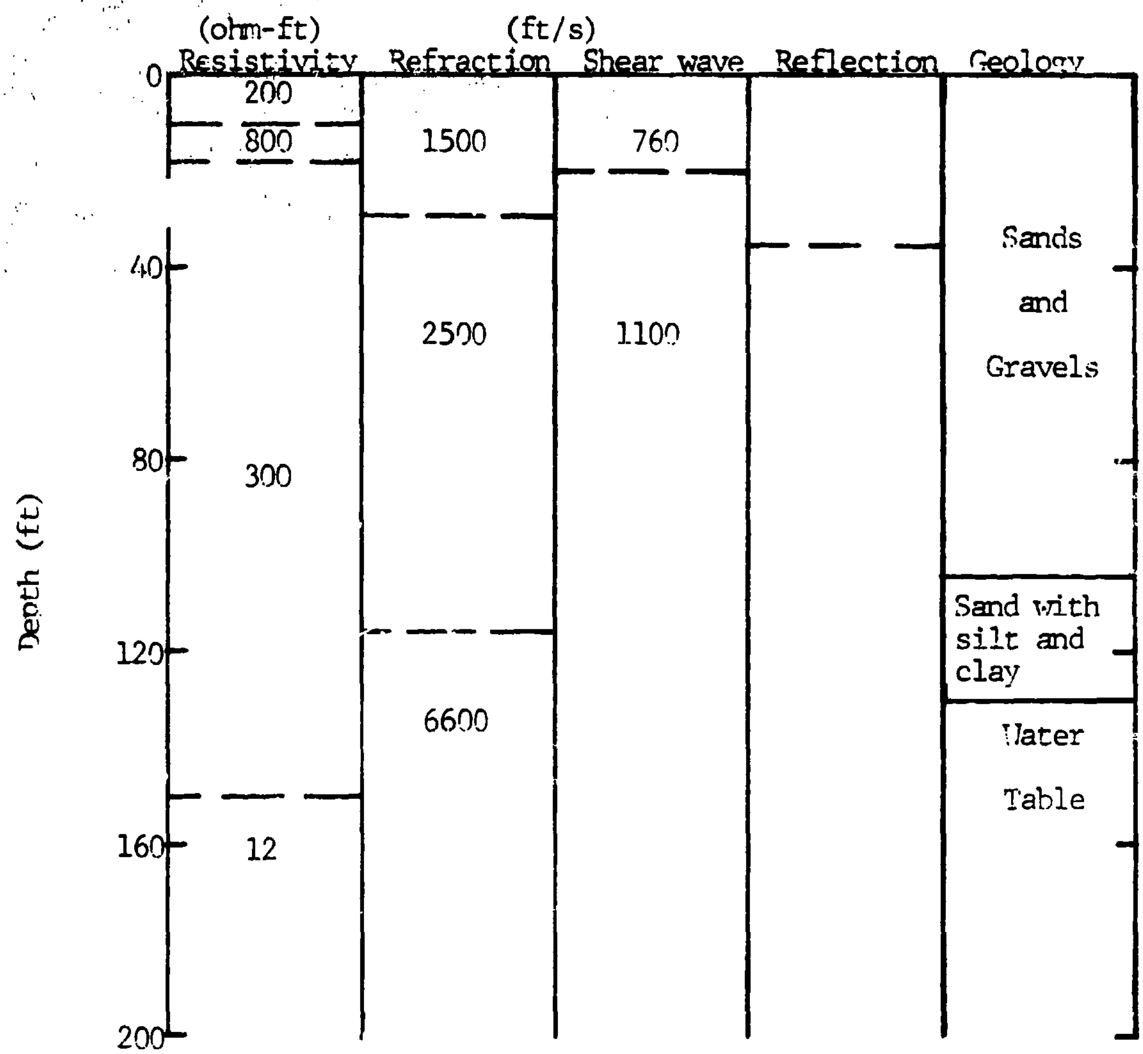

Figure 25. Geophysical and geological models for T-14 line, White Sands, New Mexico.

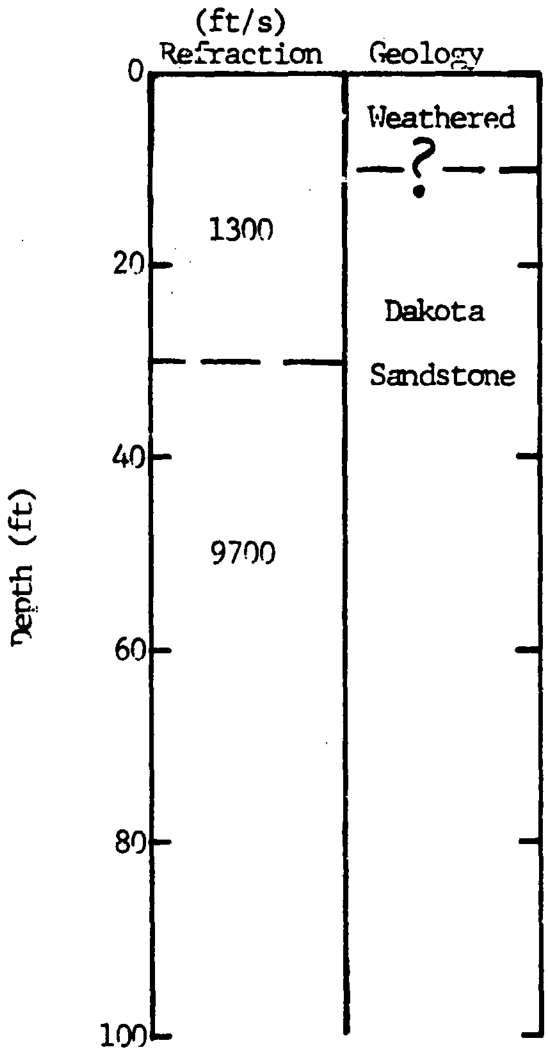

Figure 26. Geophysical and geological models for CSM-3 line, Fort Carson, Colorado.

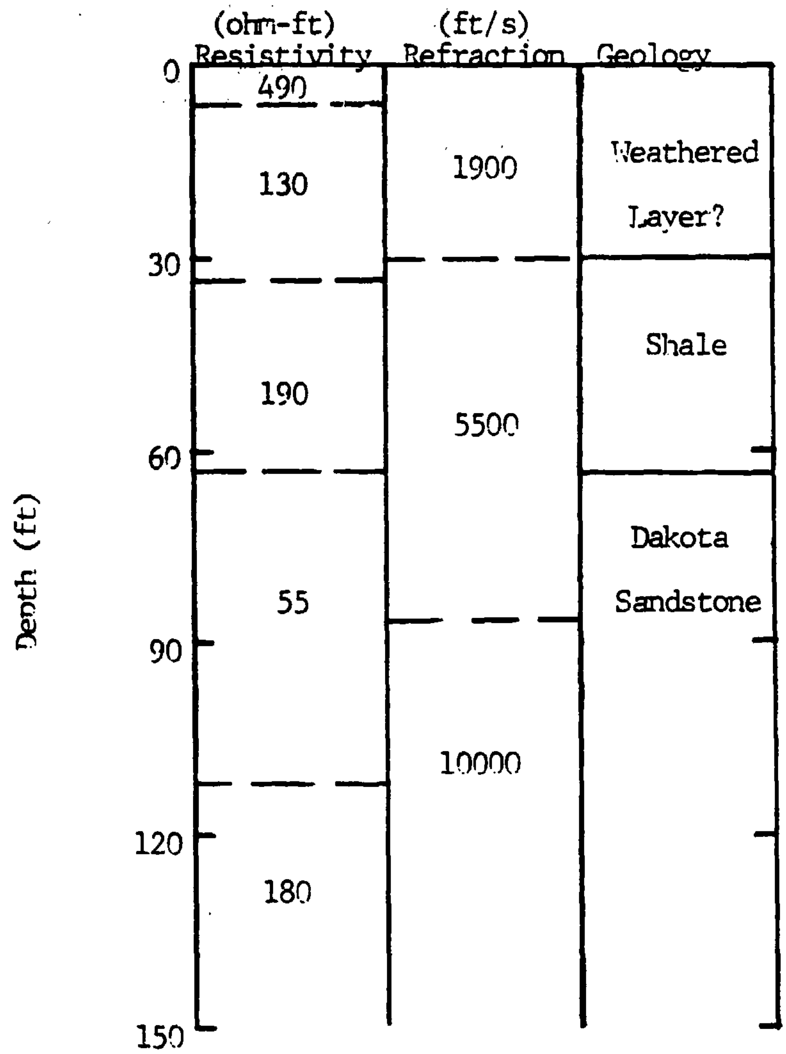

Figure 27. Geophysical and geological models for CSM-2 and WES-4 line, Fort Carson, Colorado.

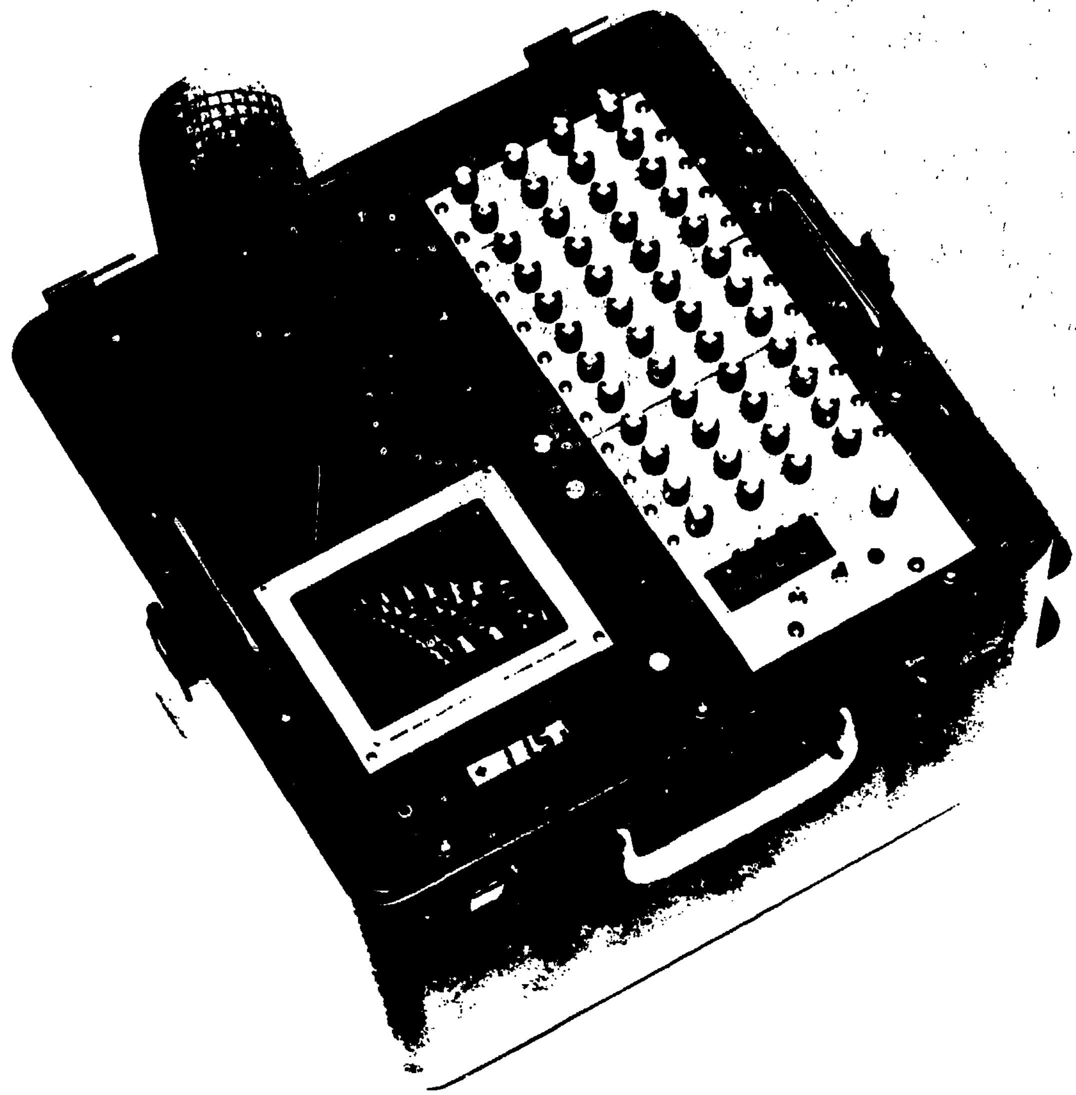

Figure 28. Seismic field equipment. Adapted after EG&G Geometrics (1982).

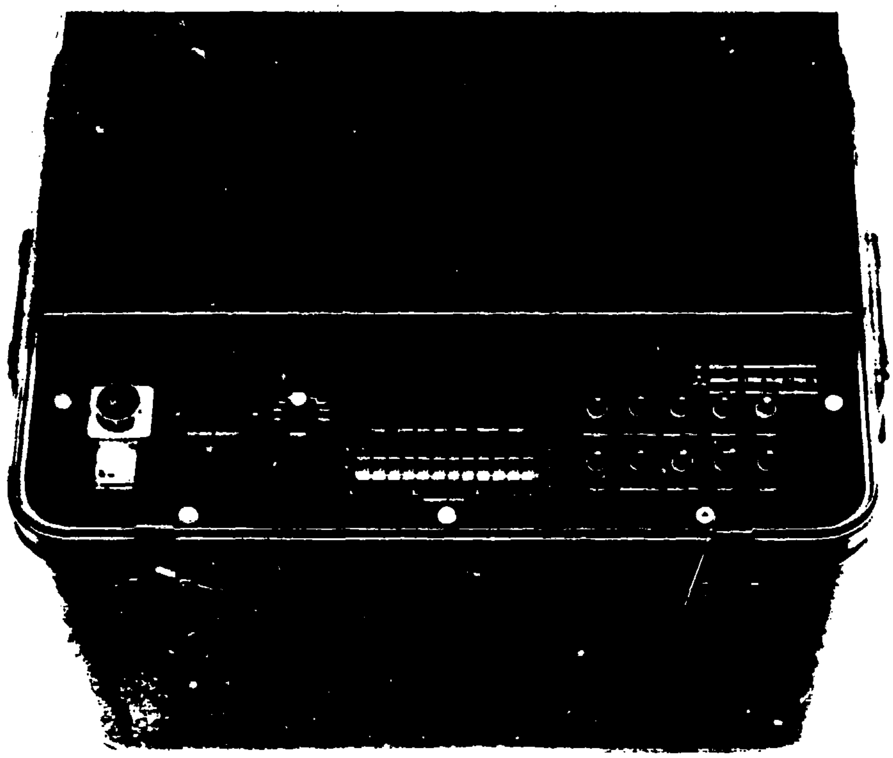

Figure 29. Digital magnetic tape recorder. Adapted after EG&G Geometrics (1982).

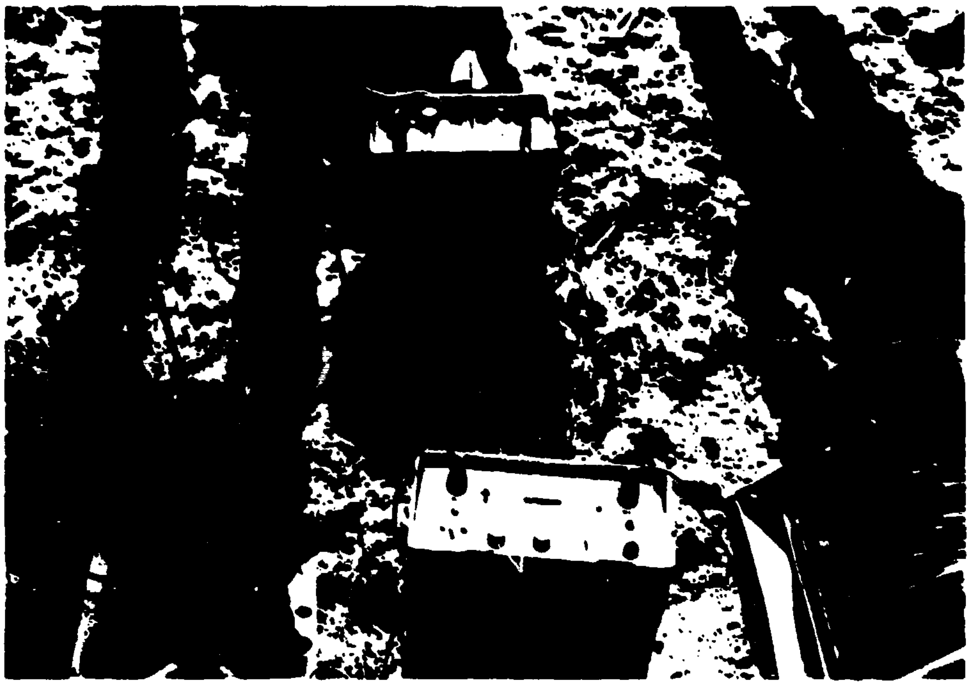

Figure 30. Electrical field equipment.

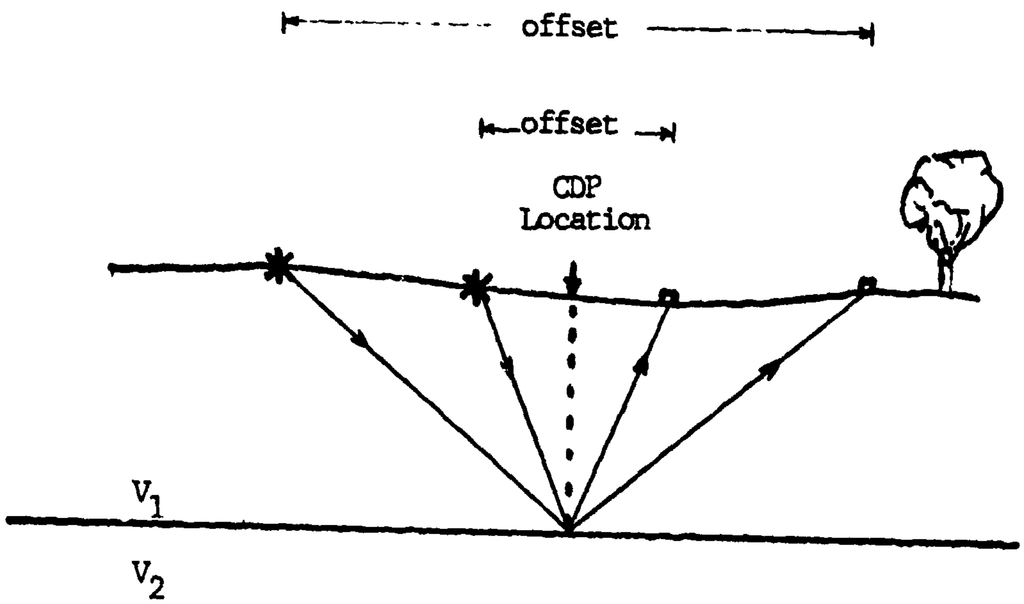

Figure 31. Common depth points.

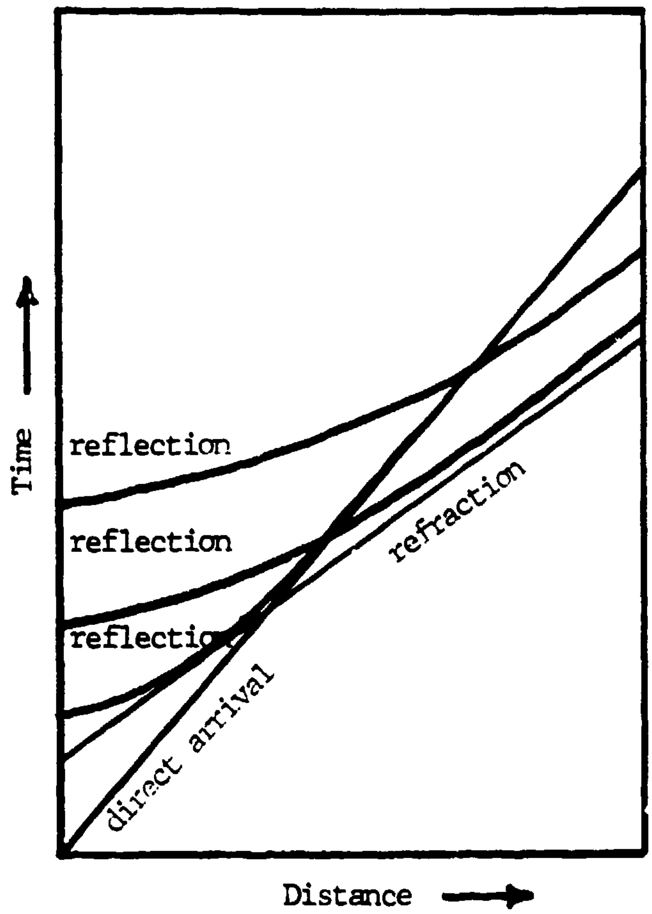

Figure 32. Seismic arrivals.

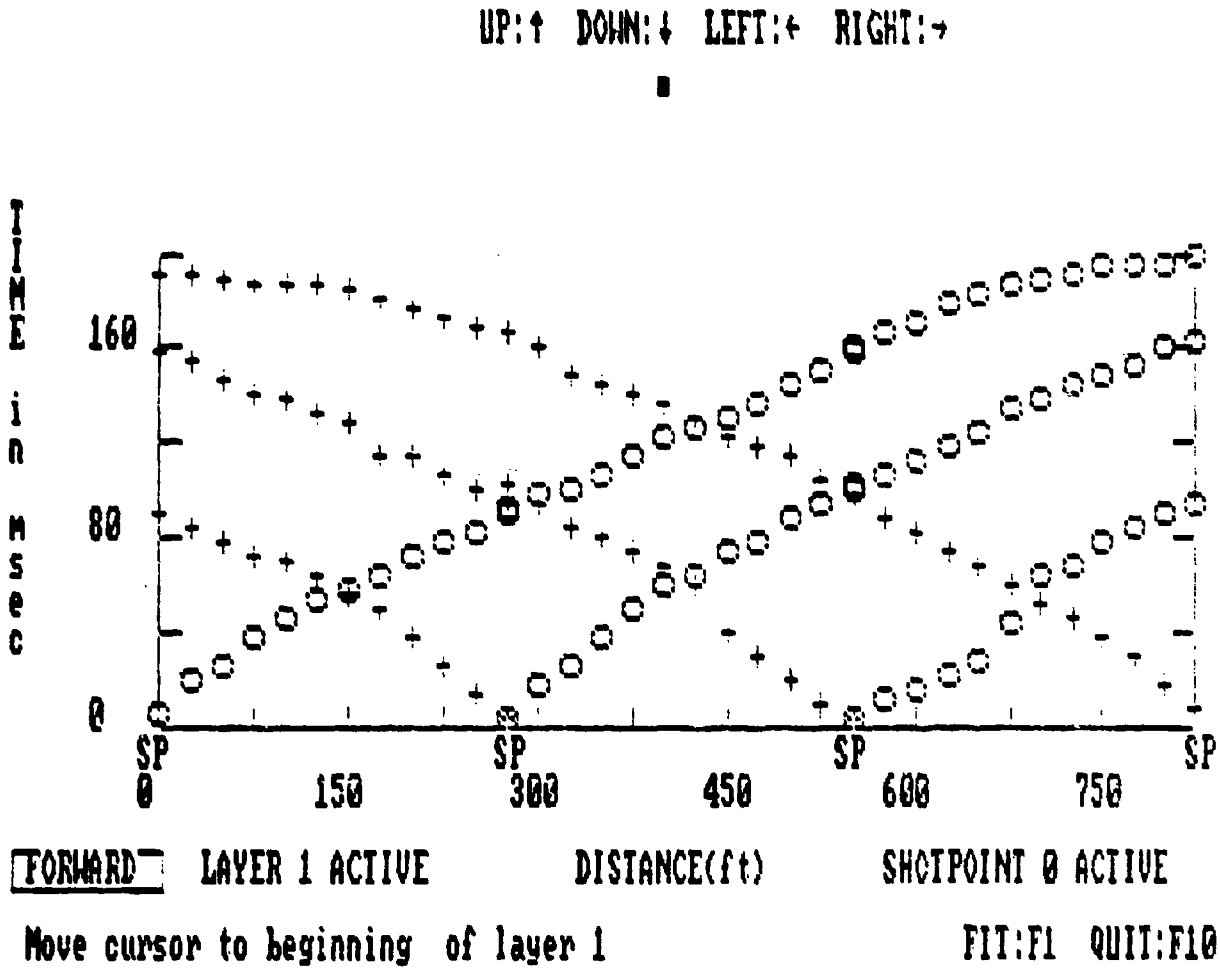

Figure 33. Computer-generated time distance plot. Circles and crosses are the refracted arrivals.

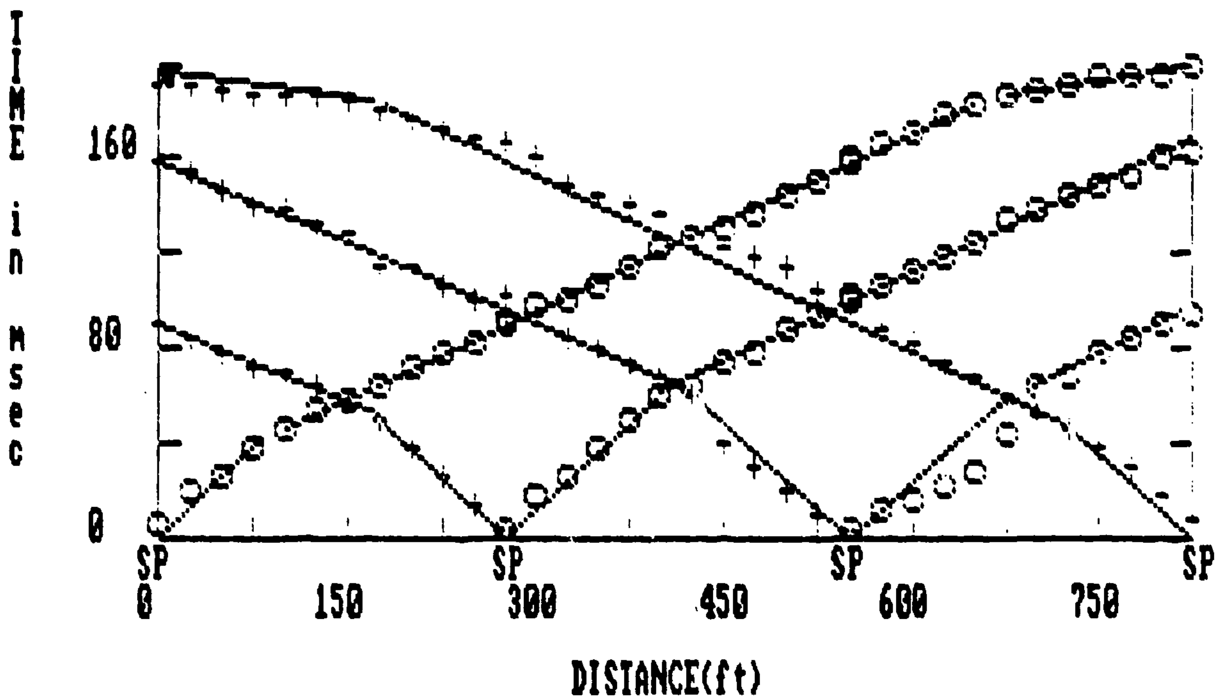

Figure 34. Computer-fitted velocity plot. Circles and crosses are the refracted arrivals. Inverse slopes of the lines are equal to the velocities.

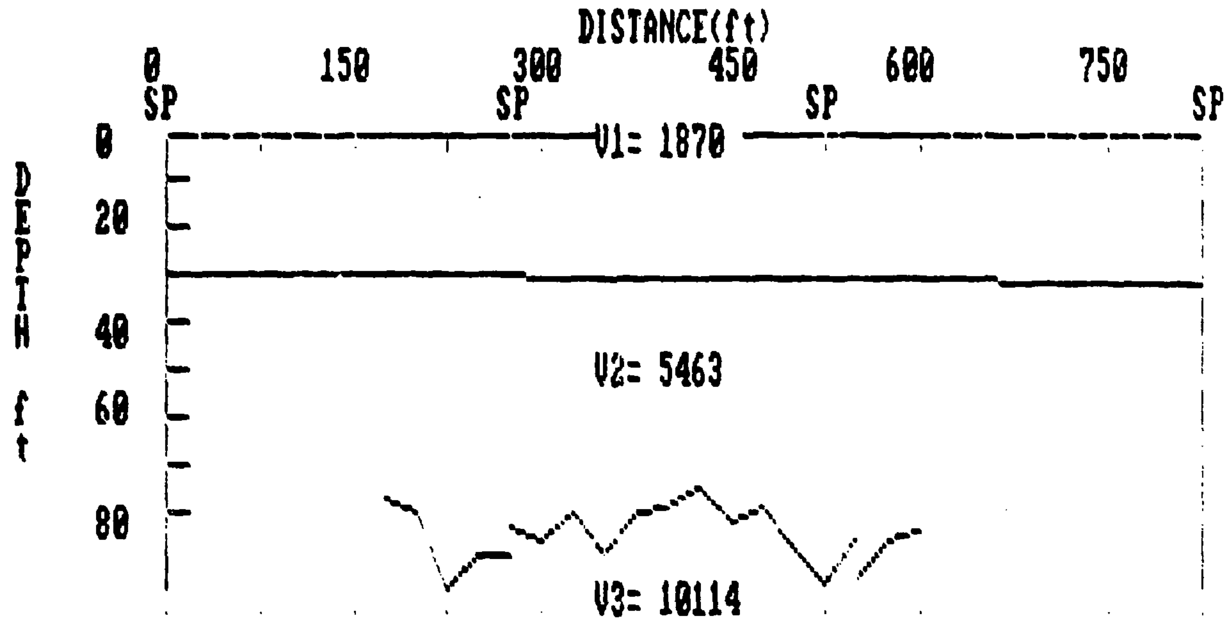

Figure 35. Computer-generated velocity model. Velocities are in ft/s.

DEPTH(ft) TO LAYER 2

0	25	50	75	100	125	150	175	200	225	250	275
25.3	25.6	25.8	26.1	26.4	26.7	27.0	27.3	27.6	27.8	28.1	28.47396
275	300	325	350	375	400	425	450	475	500	525	550
28.4	28.7	29.0	29.3	29.6	29.9	30.1	30.4	30.7	31.0	31.3	31.63269
550	575	600	625	650	675	700	725	750	775	800	825
31.6	31.9	32.2	32.4	32.7	33.0	33.3	33.6	33.9	34.2	34.5	34.79142

DEPTH(ft) TO LAYER 3

0	25	50	75	100	125	150	175	200	225	250	275
154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.5554
275	300	325	350	375	400	425	450	475	500	525	550
154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.5036
550	575	600	625	650	675	700	725	750	775	800	825
154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.	154.4519

V1= 2094 ft/sec V2= 4078 ft/sec V3= 11046 ft/sec

Figure 36. Computer-generated depth table. Boxed numbers are geophone locations. Unboxed numbers are depths.